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RESEARCH ARTICLE

Exogenous application of mepiquat chloride and crop geometry alters cotton growth and yield traits of compact cotton cultivars (*Gossypium hirsutum* L.)

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Abstract

Mepiquat chloride is widely used as a growth regulator in cotton fields to increase crop yield. The present study investigated the effects of growth regulator (mepiquat chloride) and row spacings on compact cotton's growth and yield attributes. An experiment was conducted during summer and winter seasons of 2023-2024 at Cotton Research Station, Veppanthattai and the field trial was designed as a split-split plot with three main plots (Varieties - CO 17, VPT 2, Suraksha), four sub-plots (crop geometry - 90 x 15 cm, 70 x 15 cm, 90 x 10 cm, 70 × 10 cm), and two sub-sub plots (growth regulators - mepiquat chloride @150 ppm, mepiquat chloride + cyclanilide @400 ppm), each replicated three times. Results concluded that the Suraksha variety showed superior performance with greater plant height, higher biomass, more sympodial branches, higher bolls/m^2 and higher seed cotton yield than CO 17 and VPT 2. Wider spacing of 90 cm resulted in greater plant height, more sympodial branches and more bolls/m^2 to a significantly rise in dry matter production due to the higher number of plants per unit area. Combining mepiquat chloride with cyclanilide at 400 ppm during square initiation and boll development stages significantly increased sympodial branches and bolls/m2, improving seed cotton yield.

In contrast, applying mepiquat chloride alone led to more significant biomass accumulation, increased plant height and longer internodal distances. It was suggested that the Suraksha variety be sown at a spacing of 90 x 15 cm and treated with a combination of mepiquat chloride and cyclanilide. This resulted in a plant architecture well-suited for mechanical harvesting.

Keywords

compact cotton; crop geometry; mepiquat chloride; growth; HDPS; seed cotton yield

Introduction

Cotton (*Gossypium hirsutum* L.), widely known as "White Gold," is a crucial fiber crop that plays a significant role in the global economy, cultivated in approximately 80 countries. The top cotton-producing countries, including China, India, the USA, Brazil and Pakistan, collectively account for 75.4% of global cotton production. Among these, India plays a significant role in cultivating cotton to an area of about 13.48 million hectares and producing 36.5 million bales, constituting 32% of total global output. During 2021-22, India produced 5.90 million tons (equivalent to 36.22 million bales of 170 kg each), with an average productivity rate of 523 kg/ha, compared to the global output of 25.73 million tons and a productivity rate of 775 kg/ha. Cotton meets the global demand for fibre and accounts for 16-24% of the world's edible oil production (1). Due to its indeterminate growth habit, cotton is highly sensitive to environmental conditions and agricultural practices, which include variety selection, sowing date and method, plant spacing, water management, seed treatment and proper fertilizer application. These factors are vital for maximizing cotton's growth, development, and yield potential (2). However, the spreading growth habit of cotton crops increases the labour required for cultivation, necessitating strategies such as using genetically modified varieties and implementing optimized canopy architecture to control excessive vegetative growth (3). Modern cotton varieties, typically long-duration, tall-growing plants with extended sympodial growth, increase cultivation costs due to the need for more manual pickings. Since cotton cultivation is labour-intensive, developing compact genotypes is particularly valuable. These genotypes are ideal for dense planting suited for machine picking due to their short stature, limited vegetative growth, shorter fruiting branches, closer inter-branch and inter-boll distances, and synchronous maturity, allowing for harvest in just two or three pickings. Compact genotypes, altered crop geometry, growth regulators, and need-based fertilizer application make HDPS more suitable for mechanized cultivation in India (4,5). To enhance productivity, optimize profits and make management decisions amidst rising production costs, adopting a high-density planting system (HDPS) is a promising alternative (6).

HDPS involves increasing plant density to 1-2 lakh plants per hectare by reducing the intra-row spacing to as low as 30 cm (7). Most of the growing cotton countries, such as Brazil, China, Australia, Spain, Argentina and Greece, evaluated, validated and implemented cotton's narrow row planting system to increase productivity. This system modifies crop geometry, allowing more plants per hectare, each producing an average of 8 to 14 bolls using genetically modified varieties (8). Although closer spacing generally leads to higher yields, it also increases competition for resources, potentially leading to smaller plants with efficient resource use but reduced boll load and delayed leaf senescence. HDPS, particularly beneficial in low-fertility fields, has been recommended as an alternative to traditional methods for improving yield and input use efficiency. Establishing the appropriate plant stand is crucial for maximizing yield, as lower densities may lead to resource wastage, while higher densities could restrict individual plant growth. Crop geometry significantly impacts seed cotton yield, with closer spacing generally resulting in higher yields (9). HDPS helps improve light interception, efficient leaf area development and early canopy closure, which helps shade weeds and reduce their competitiveness. Additionally, HDPS promotes synchronized flowering, uniform boll bursting, and earlier maturity, contributing to increased productivity and profitability, better input use efficiency and reduced risks in current cotton production practices in India (10).

Natural plant growth regulators (PGRs), such as auxins, gibberellins and cytokinins, have been studied for their effects on cotton growth, promoting root development, stem elongation and stress responses. However, their effects are often inconsistent due to environmental variability. In contrast, mepiquat chloride (MC), a synthetic PGR, provides more predictable control of cotton growth by inhibiting gibberellin synthesis, resulting in shorter, more manageable canopy structures and improved fruit retention. The consistent performance of mepiquat chloride makes it favourable under high-density cotton farming. Still, its potential environmental risks include soil persistence, water contamination, and possible impacts on non-target organisms and soil microbes. While mepiquat chloride is effective, integrating natural PGRs and reducing synthetic inputs could mitigate long-term environmental harm. PGRs like mepiquat chloride and cyclanilide also significantly optimize cotton production by regulating canopy structure, enhancing boll retention, and improving fiber quality (11). Mepiquat chloride, commonly used to control excessive vegetative growth, enhances nutrient absorption and boosts crop productivity by inhibiting gibberellic acid synthesis. Specifically, mepiquat chloride blocks the conversion of geranylgeranyl diphosphate to ent-kaurene, influencing the distribution of assimilates, remobilization of reserves, and the uptake and transport of nutrients. This process reduces cell division and enlargement, decreasing plant height, the number of nodes on the main stem, internodal distance, and leaf expansion while increasing light-use efficiency and crop productivity (12;13;14). This results in a more compact plant architecture better suited for mechanized harvesting and higher yields (15). Given the labour-intensive nature of cotton cultivation, particularly in India, adopting HDPS combined with PGR application and compact genotypes offers a promising strategy for enhancing productivity and profitability while reducing cultivation costs. Therefore, the present study was conducted to determine the optimum plant spacing and growth regulators in different cotton cultivars with the recommended dose of fertilizer on the impact of cotton growth and their yield attributes.

Materials and Methods

Experimentation Details

Two field experiments were conducted at the Cotton Research Station of Tamil Nadu Agricultural University in Veppanthattai (latitude 11°34' N, longitude 78°80' E) during the summer and winter of 2023-24. The experiments followed a split-split plot design involving three factors with three replications. Main Plots - Varieties (V1: CO 17, V2: VPT 2, V3: Suraksha), Sub-Plots - Plant Spacings (S1: 90 x 15 cm, S2: 70 x 15 cm, S3: 90 x 10 cm, S4: 70 × 10 cm), Sub-Sub Plots - Plant Growth Regulators (G1:

Mepiquat chloride @150 ppm, G2: Mepiquat chloride + cyclanilide @ 400 ppm). The plant growth regulators were applied at square initiation and boll formation stages. The selected cultivars featured a compact plant type with zero monopodia and short sympodial length, making them suitable for High-Density Planting Systems (Table 1). Pre-sowing soil analysis is presented in Table 2.

Crop Management

Sowing was done using a pneumatic precision planter with a 10 kg/ha seed rate. The generally recommended fertilizer dose for HDPS was 100:50:50 NPK kg/ha. Nitrogen and potassium were applied in two equal splits, one during seedbed preparation and the other at the start of flowering. Phosphorus was broadcast during seedbed preparation. Irrigation was provided three days after sowing, followed by crop-need-based irrigation. Pre-emergence weed control was managed with Pendimethalin 30% EC at 3.3 l/ha, followed by a power weeder at 25 and 45 days after sowing (DAS). To control sucking pests, the following insecticides were applied at 45 and 65 DAS using a tractor-mounted boom sprayer: Acephate 75% SP @ 20 g/10 litres of water, Imidacloprid 17.8% SL @ 40 ml/10 liters of water, Fipronil 5% SC @ 30 ml/10 liters of water. These pesticides were chosen for their complementary modes of action, targeting the nervous systems of pests through systemic and contact activity, providing broad-spectrum control and minimizing resistance development. Dropp Ultra @ 250 ml/ha was applied as a defoliant to promote earliness, better boll retention and facilitate mechanical harvesting. Mechanical harvesting was performed using a spindle-type cotton harvester.

Data Collection

Growth and yield parameters were recorded by randomly selecting and labelling ten plants in each experimental plot. The following growth parameters were measured: plant height, number of monopodial and sympodial branches, length of sympodia, and internodal distance between the third and fourth nodes. Harvested bolls were air-dried to achieve moisture content below 11%, and the average boll weight was calculated. Seed cotton was picked from the plot and the yield was converted into kilograms per hectare (kg/ha). Each plot consisted of 20 m long, 8 rows and 6 rows with inter-row spacing of 70 cm and 90 cm and intra-row 10 cm and 15 cm, respectively. The harvestable boll percentage measures how many bolls on a cotton plant are mature and ready for harvesting. The harvest index is calculated as the ratio of economic yield (harvested product) to the total above-ground biomass produced by the plant (16).

$$\text{Harvest Index (HI)} = \frac{\text{Economic Yield}}{\text{Biological Yield}}$$

$$\text{Harvestable Boll (\%)} = \frac{\text{Number of Harvestable Bolls}}{\text{Total Number of Bolls}} \times 100$$

$$\text{Link yield (kg/ha)} = \frac{\text{Link Weight (kg)}}{\text{Area harvested (ha)}}$$

$$\text{Biological yield} = \text{stalk yield} + \text{seed cotton yield}$$

The collected data were subjected to statistical analysis of variance (ANOVA). The least significant difference (LSD) test was employed to analyze the mean square errors. This procedure calculates a single LSD value at a 5% significance level, the threshold for determining significant versus non-significant differences between treatment means (17).

Table 1. Characteristics of tested cotton cultivars

S. No.	Character	Suraksha	CO 17	VPT 2
1.	**Parentage**	Surabhi × (MCU5 × Z2)	Khandwa 2 × LH 2220	Suraj × TCH 1819
2.	**Salient Features**	Semi-compact suitable for HDPS. Resistant to Bacterial Leaf Blight, Grey Mildew, Root Rot, Tobacco streak virus, Jassids, whitefly, Thrips, Aphids and Mirid Bug.	Compact plant type suitable mechanized harvest. Possesses zero monopodia with short sympodial length. Ideal for high-density planting systems.	Resistant to sucking pests, tolerant to drought and remains green till maturity, synchronized boll maturity, suitable for rainfed conditions, Compact plant type suitable mechanized harvest.
3.	**Duration (days)**	140-145	125-130	130-135
4.	**Seed cotton yield (kg/ha)**	2600	2361	2300
5.	**Ginning outturn (%)**	34	35	34
6.	**2.5 % span length (mm)**	32.4	27	30.4
7.	**Micronaire (10 g/inch)**	3.7	4.3	4.3
8.	**Fibre strength (g/tex)**	34.3	26.8	30.3
9.	**Spinable counts**	60 counts	40 counts	40 counts
10.	**Released by**	CICR, Coimbatore	TNAU, Coimbatore	CRS, Veppanthattai

Results

Growth Parameters

The analysis of growth data revealed significant differences among the varieties when sown under various plant spacings and treated with different growth regulators, as detailed in Table 2.

Plant Height: Among the compact cotton varieties, CO 17 (V1) registered significantly maximum plant heights during summer and winter. CO 17 (V1) reached maximum heights of 89.1 cm and 90.6 cm at harvest during both summer and winter. Similarly, Suraksha (V3) recorded 83.2 cm and 96.2 cm at harvest during both summer and winter. The CO 17 variety exhibited the most significant plant height during the summer, while the Suraksha variety led in the winter. Pooled data showed that CO 17 and Suraksha were 4.7% and 4.5% taller than the VPT 2 variety. The study also evaluated the impact of plant spacing on height and revealed that plants spaced at 90 x 15 cm were found to be taller, surpassing those spaced at 70 x 15 cm, 90 x 10 cm, and 70 × 10 cm by 4.6%, 8.6% and 13.6%, respectively. Additionally, the application of mepiquat chloride at 150 ppm resulted in plants being 7.6% taller than those treated with a combination of mepiquat chloride and cyclanilide at 400 ppm.

Monopodia and Sympodial Branches: The number of monopodial branches significantly differed with compact varieties, with Suraksha having more monopodial branches than VPT 2 and CO 17. Also, the result indicated no significant effect on plant spacing or growth regulators. It was also found that 90 cm row spacing had higher monopodial branches than 70cm. The Suraksha variety exhibited the highest number of sympodial branches, statistically similar to CO 17, while CO 17 was comparable to VPT 2. Wider row spacing of 90 x 15 cm resulted in 19.3% more sympodial branches than the narrower spacing of 70 x 10 cm. The use of mepiquat chloride and cyclanilide @ 400 ppm led to a significant increase in the number of sympodial branches per plant, with values of 23.7 during the summer and 25.8 during the winter, compared to mepiquat chloride @ 150 ppm alone. Pooled data of sympodial length indicated no significant difference in sympodial length across different varieties, plant spacings, or plant growth regulators (PGRs).

Internodal Distance: There was no significant difference in internodal distance among the compact varieties, with the average internodal distance being 3.7 cm across the study. No significant variation in internodal distance was observed across different plant spacings. Applying mepiquat chloride @ 150 ppm resulted in a 10.2% longer internodal length than combining mepiquat chloride and cyclanilide @ 400 ppm.

Table 2. Physico-chemical properties of the initial soil sample of the experimental site

Particulars	Method	Summer, 2023	Winter, 2023
A. Mechanical analysis			
Clay (%)	International pipette method	60.7	63.0
Silt (%)		17.7	16.1
Coarse sand (%)		13.9	13.5
Fine sand (%)		7.8	7.5
Textural class - Clay loam			
B. Physical properties			
Gravel (%)	International pipette method	8.3	6.2
Pore space (%)		33.7	34.7
Bulk Density (Mg m^{-3})		1.45	1.49
C. Electro-chemical properties			
pH	Potentiometry (soil: water=1: 2.5)	8.46	8.56
Electrical Conductivity	Conductometry (1:2.5 soil water suspension)	0.12	0.15
D. Chemical properties			
Available nitrogen (kg ha^{-1})	Alkaline permanganate method	177.5	170.4
Available phosphorus (kg ha^{-1})	0.5M $NaHCO_3$ extraction colorimetric method	24.9	22.8
Available potassium (kg ha^{-1})	Flame photometric method using neutral normal ammonium acetate extract	185.0	190.7
Organic carbon (g kg^{-1})	Chromic acid wet digestion method	5.2	4.2

Table 2. Effect of different compact cotton varieties, crop geometry and plant growth regulators on growth attributes under high-density planting system in summer 2023 (season I) and winter 2023-24 (season II)

Treatments	Plant height (cm)			Monopodial branches/plant			Sympodial branches/plant			Length of sympodial branches (cm)			Internodal distance (cm)			Total above-ground biomass (g m^{-2})		
	S I	S II	P	S I	S II	P	S I	S II	P	S I	S II	P	S I	S II	P	S I	S II	P
Compact Variety																		
V_1- CO 17	89.1	90.6	89.8	0.16	0.16	0.16	24.0	23.4	23.6	18.0	18.3	18.2	3.6	3.6	3.6	1264.8	1343.6	1304.2
V_2- VPT 2	82.0	89.2	85.6	0.20	0.30	0.25	20.2	22.5	21.3	18.9	18.7	18.8	4.0	3.8	3.9	1085.2	1169.8	1127.5
V_3- Suraksha	83.2	96.2	89.9	0.40	0.50	0.45	24.2	25.7	25.0	17.2	17.7	17.4	3.6	3.5	3.6	1215.3	1363.5	1289.4
SEd	2.0	2.0	1.6	0.05	0.09	0.07	1.2	1.2	1.2	1.6	1.6	1.6	0.4	0.2	0.2	16.0	38.1	26.3
CD (p=0.05)	5.4	5.2	3.5	0.15	0.24	0.20	2.0	2.0	2.0	NS	NS	NS	NS	NS	NS	44.6	105.8	73.0
Crop Geometry																		
S_1- 90 × 15 cm	92.2	97.2	94.7	0.33	0.38	0.35	25.0	27.6	26.5	19.2	19.3	19.2	3.3	3.6	3.5	1000.0	1117.6	1058.8
S_2- 70 × 15 cm	87.2	93.7	90.4	0.27	0.33	0.30	22.3	22.0	22.1	17.0	17.2	17.2	3.9	3.6	3.8	1114.8	1205.5	1160.2
S_3- 90 × 10 cm	81.4	91.7	86.5	0.22	0.27	0.25	23.2	25.0	24.1	18.6	18.9	18.7	3.7	3.8	3.7	1286.8	1381.6	1334.2
S_4- 70 × 10 cm	78.4	85.3	81.8	0.22	0.27	0.25	20.4	20.8	20.6	17.3	17.5	17.4	4.2	3.6	3.9	1351.9	1464.6	1408.3
SEd	2.3	2.7	1.8	0.20	0.20	0.20	0.9	0.9	0.9	1.8	1.8	1.8	0.2	0.2	0.1	17.0	22.3	18.7
CD (p=0.05)	4.8	5.6	3.9	NS	NS	NS	2.0	2.0	1.9	NS	NS	NS	0.4	NS	0.2	35.5	46.8	39.3
Plant Growth Regulators																		
G_1 – MC @150 ppm	88.5	95.3	91.8	0.27	0.36	0.32	21.7	22.7	22.2	17.2	17.4	17.3	4.0	3.8	3.9	1231.5	1340.2	1285.8
G_2 – MC+C @400 ppm	81.1	88.7	84.9	0.25	0.28	0.26	23.7	25.0	24.4	18.9	19.0	18.9	3.6	3.4	3.5	1145.3	1244.5	1194.9
SEd	1.2	1.3	1.0	0.09	0.10	0.10	0.7	0.8	0.7	1.0	1.2	1.0	0.2	0.2	0.1	13.0	13.5	12.6
CD (p=0.05)	2.5	2.7	2.0	NS	NS	NS	1.5	1.6	1.4	NS	NS	NS	0.3	0.4	0.3	26.7	27.9	26.2
Interaction	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	S	S	S

(MC- Mepiquat chloride; MC+C- Mepiquat chloride + Cyclanilide)

Total biomass (g m^{-2}): The impact of compact cotton varieties, plant spacings and plant growth regulators on total above-ground biomass are given in Table 1. Significant variation in biomass content was observed across different compact cotton varieties and plant spacings. Suraksha and CO 17 accumulated 12.6% and 13.6% more total above-ground biomass than VPT 2. Regarding plant spacings, plants sown with spacing of 70 x 10 cm significantly recorded the maximum biomass accumulation of 1408.3 g m^{-2}, followed by 90 x 10 cm (1381.6 g m^{-2}), 70 x 15 cm (1205.5 g m^{-2}) and 90 x 15 cm (1117.6 g m^{-2}). It was found that narrow row spacing of 70 x 10 cm accumulated 24.8%, 17.6% and 7.0% more biomass than spacings of 90 x 15 cm, 70 x 15 cm and 90 x 10 cm, respectively. A significant variation in biomass content was observed across plant growth regulators. It was found that cotton plants treated with mepiquat chloride @ 150 ppm alone produced 7.0% more total above-ground biomass than combined application of mepiquat chloride and cyclanilide @ 400 ppm. The interaction component for all three variables was found to be non-significant.

Yield Attributes

Significant differences in boll numbers, boll weight, seed cotton yield and stalk yield were observed among the compact cotton varieties, different plant spacings and growth regulators, as summarized in Tables 3 and 4.

Boll characters: The effect of different compact cotton varieties, crop geometry and plant growth regulators on boll attributes under a high-density planting system were presented in Table 3. The Suraksha variety produced the highest number of bolls, with 69.5 bolls/m^2 and had an average boll weight of 4.1 g, whereas the harvestable percentage was higher with VPT 2 (86.5%). The wide spacing of 90 x 10 cm row spacing resulted in the highest boll number per square meter (71.4 bolls/m^2), which was statistically similar to the 90 x 15 cm spacing (69.7 bolls/m^2), followed by the 70 x 15 cm and 70 x 10 cm spacings. Higher boll weight was recorded with the 90 x 15 cm and 70 × 15 cm spacings, both at 4.1 g, followed closely by the 90 x 10 cm and 70 x 10 cm spacings. There was no significant difference in harvestable percentage with plant spacings. Applying mepiquat chloride and cyclanilide @ 400 ppm resulted in 68.2 bolls/m^2 and significantly increased boll weight by 9.5% compared to mepiquat chloride @ 150 ppm alone. There was no significant difference in harvestable percentage with plant growth regulators.

Table 3. Effect of different compact cotton varieties, crop geometry and plant growth regulators on bolls attributes under high-density planting system in summer 2023 (season I) and winter 2023-24 (season II)

Treatments	Bolls/plant			Bolls/m²			Single boll weight			10 boll weight			Harvestable boll %		
	S I	S II	P	S I	S II	P	S I	S II	P	S I	S II	P	S I	S II	P
Compact Variety															
V_1- CO 17	8.3	8.2	8.2	72.1	65.5	68.9	3.8	4.0	3.8	36.2	37.5	36.8	81.1	84.0	82.5
V_2- VPT 2	8.2	8.3	8.2	65.2	65.6	65.5	4.0	4.0	3.9	37.1	38.3	37.7	88.8	84.2	86.5
V_3- Suraksha	8.7	9.5	9.0	70.8	67.3	69.5	4.1	4.2	4.1	41.1	41.8	41.4	82.6	82.0	82.3
SEd	0.3	0.6	0.4	1.3	1.5	1.2	0.03	0.04	0.03	0.2	0.4	0.3	2.7	2.0	1.3
CD (p=0.05)	NS	NS	NS	3.5	NS	NS	0.08	0.11	0.09	0.4	1.2	0.7	NS	NS	NS
Crop Geometry															
S_1- 90 × 15 cm	11.5	11.8	11.6	70.9	68.6	69.7	4.1	4.2	4.1	40.1	41.1	40.6	84.9	83.8	84.1
S_2- 70 × 15 cm	8.6	9.0	8.7	67.6	63.7	65.6	4.1	4.2	4.1	38.8	40.0	39.5	84.3	83.5	84.0
S_3- 90 × 10 cm	8.0	8.0	7.8	73.2	69.5	71.4	3.8	3.9	3.8	37.5	38.5	38.0	84.0	83.2	83.5
S_4- 70 × 10 cm	5.5	6.0	5.7	66.2	62.8	64.5	3.8	3.8	3.8	36.1	37.1	36.6	83.5	83.0	83.5
SEd	0.4	0.5	0.3	1.4	1.8	1.5	0.06	0.05	0.04	0.2	0.3	0.7	2.1	2.5	2.0
CD (p=0.05)	0.9	1.0	0.6	3.0	4.0	3.2	0.12	0.11	0.09	0.3	0.6	0.16	NS	NS	NS
Plant Growth Regulators															
G_1 – MC @150 ppm	7.8	7.7	7.7	69.3	65.1	67.3	3.8	3.8	3.8	35.6	36.6	36.1	83.9	83.2	83.6
G_1 – MC + C @400 ppm	9.0	9.6	9.2	69.6	67.3	68.2	4.2	4.2	4.2	40.6	41.8	41.2	84.4	83.5	84.0
SEd	0.3	0.3	0..2	1.0	0.9	0.7	0.05	0.04	0.04	0.1	0.3	0.5	1.7	1.2	1.0
CD (p=0.05)	0.6	0.6	0.5	NS	NS	NS	0.11	0.09	0.08	0.2	0.7	0.11	NS	NS	NS
Interaction	NS	NS	NS	S	S	S	NS	NS	NS	S	S	S	NS	NS	NS

(MC- Mepiquat chloride; MC+C- Mepiquat chloride + Cyclanilide)

Table 4. Effect of different compact cotton varieties, crop geometry and plant growth regulators on yield attributes under high-density planting system in summer 2023 (season I) and winter 2023-24 (season II)

Treatments	Seed cotton yield (kg/ha)			Stalk yield (kg/ha)			Biological yield (kg/ha)			Lint yield (kg/ha)			Harvest index		
	S I	S II	P	S I	S II	P	S I	S II	P	S I	S II	P	S I	S II	P
Compact Variety															
V_1- CO 17	2256	2178	2217	3805	3990	3897	6061	6168	6115	870	808	839	0.37	0.35	0.36
V_2- VPT 2	2167	2171	2169	3299	3476	3387	5467	5647	5557	825	777	801	0.39	0.38	0.39
V_3- Suraksha	2415	2348	2382	3676	4031	3854	6092	6379	6236	925	815	870	0.39	0.37	0.38
SEd	27	29	23	53	140	94	47	139	85	10	8	7	0.08	0.09	0.07
CD (p=0.05)	76	82	64	149	390	261	132	386	236	26	22	17	NS	NS	NS
Crop Geometry															
S_1- 90 x 15 cm	2421	2405	2413	3124	3461	3293	5546	5866	5706	923	860	887	0.43	0.41	0.42
S_2- 70 x 15 cm	2310	2260	2285	3499	3853	3676	5809	6114	5961	914	824	865	0.39	0.37	0.38
S_3- 90 x 10 cm	2303	2255	2279	3649	3774	3711	5952	6030	5991	862	806	843	0.38	0.37	0.38
S_4- 70 x 10 cm	2084	2010	2047	4102	4240	4171	6186	6250	6218	794	711	752	0.33	0.32	0.33
SEd	30	40	29	59	65	62	60	64	58	14	13	10	0.05	0.06	0.06
CD (p=0.05)	64	84	68	124	137	130	126	135	123	29	27	20	0.11	0.13	0.12
Plant Growth Regulators															
G_1 – MC @150 ppm	2184	2151	2167	3822	4066	3944	6006	6217	6112	841	763	802	0.36	0.34	0.35
G_1 – MC + C @400 ppm	2375	2314	2345	3365	3598	3481	5740	5912	5826	905	837	871	0.41	0.39	0.40
SEd	15	22	11	43	45	44	50	53	50	7	8	5	0.02	0.03	0.02
CD (p=0.05)	30	46	25	89	93	91	105	110	102	15	17	10	0.05	0.06	0.05
Interaction	S	S	S	NS	NS	NS	NS	NS	NS	S	S	S	S	S	S

(MC- Mepiquat chloride; MC+C- Mepiquat chloride + Cyclanilide)

Seed cotton yield: Pooled data confirmed that Suraksha outperformed the CO 17 and VPT 2 varieties by 7.0% and 9.0%, respectively, in seed cotton yield with an average lint yield of 870 kg/ha. The highest seed cotton yield with a mean of 2,413 kg/ha was achieved with the 90 x 15 cm spacing with an average lint yield of 887 kg/ha, followed by the 70 x 15 cm spacing, which was comparable to the 90 x 10 cm spacing during two cropping seasons. The pooled data of the combined application of mepiquat chloride and cyclanilide @ 400 ppm resulted in 7.6% more seed cotton yield than mepiquat chloride @ 150 ppm alone.

Stalk yield: Pooled data showed that CO 17 produced the maximum stalk yield of 3897 kg/ha, comparable to Suraksha's (3854 kg/ha). Similarly, the biological yield was higher in Suraksha (6236 kg/ha) than in CO 17 (6115 kg/ha). The highest stalk yield and biological of 4171 kg/ha and 6218kg/ha was achieved with the 70 x 10 cm spacing, followed by the 70 x 15 cm spacing and the least was obtained with 90 x 15 cm spacing. The application of mepiquat chloride @ 150 ppm alone resulted in 3944 kg/ha and 6112 kg/ha of stalk and biological yield compared to mepiquat chloride and cyclanilide @ 400 ppm (3481 kg/ha and 5826 kg/ha).

Harvest index: The harvest index (HI) showed that plant spacing and growth regulators were significantly influenced by the treatments listed in (Table 3). Regarding the cotton varieties, the harvest index was not found to be significant. Among the plant spacing, the spacing of 90 x 15 cm significantly registered the highest harvest index of 0.42, followed by 70 x 15 cm (0.38) and it was on par with the plant spacing of 90 x 10 cm (0.38) and the lowest harvest index of 0.33 was registered under 70 x 10 cm. Among the plant growth regulators, applying mepiquat chloride and cyclanilide @ 400 ppm resulted in the highest harvest index of 0.40, followed by mepiquat chloride @ 150 ppm (0.35).

Discussion

Effect of compact cotton cultivars on growth and development

A study on compact cotton varieties found significant differences in plant height and morphological traits, primarily due to genetic factors. This variation in plant height can be attributed to genetic characteristics for taller growth combined with adequate space, which allowed the plant to reach its maximum potential height. In this case, the plant heights in winter are comparable or slightly higher than in summer, suggesting that the cooler winter temperatures may fall within the optimal range for these varieties, reducing heat stress and allowing more stable growth. Additionally, the shorter daylight hours in winter might typically slow growth. Still, Suraksha, in particular, shows better growth in winter (96.2 cm) than in summer (83.2 cm), indicating its resilience to reduced light. Compact varieties tend to have a shorter stature, with CO 17 exhibiting higher dry matter production and better yield attributes. These varieties also produce more sympodial branches linked to morphological differentiation and resource availability. It has emphasized that the efficiency of a genotype is not solely reflected by the dry matter produced but also by how effectively this dry matter is partitioned into reproductive parts (18). The study also noted that compact genotypes produced fewer sympodial branches per plant, a characteristic linked to morphological differentiation, apical dominance, plant height and resource availability. Notably, compact varieties are more efficient in harnessing solar energy and converting it into biomass, particularly in reproductive structures (19). The genetic makeup influences sympodial length, with semi-compact varieties having shorter sympodia, facilitating mechanization.

Effects of crop geometry on growth and canopy development

Planting density significantly impacts cotton growth, dry matter accumulation and yield. Wider spacing (90 cm) increases plant height and promotes sympodial branch development, while higher density (70 x 10 cm) reduces plant height and branch number. Due to increased resource availability, wider spacing positively affects traits like vegetative branches, boll numbers, plant height, branch number, boll weight and yield. Optimizing canopy structure through plant and row spacing regulates plant growth and bud/boll distribution (20). However, competition can reduce plant height, branch number and vigour. Studies consistently show that wider spacing results in more sympodial branches, supporting robust growth and higher yield potential. The total above-ground biomass increased steadily throughout all growth stages, peaking at harvest. Plants sown at a spacing of 70 x 10 cm exhibited higher dry matter accumulation than other spacings due to the increased plant density per unit area. This increased density leads to more significant overall dry matter accumulation in vegetative parts, following a linear trend. However, individual plant biomass tends to decrease under these conditions due to intensified competition for resources such as light, water and nutrients (21). The declining biomass under densely populated conditions may result from reduced plant height and disruptions in the source-sink relationship (22).

Effect of mepiquat chloride on cotton growth and development

Mepiquat chloride at 150 ppm increased plant height by 7.6% while combining MC with cyclanilide at 400 ppm reduced plant height. Plant growth inhibitors like MC reduce internodal length and vegetative growth by delaying cell division and elongation and restricting gibberellin production (23). MC reduced plant height, nodes, internodal distance, and leaf area, promoting compact growth. By inhibiting gibberellin synthesis and distribution, MC limits cell elongation, restricting vertical stem growth and leaf area (24). This helps mitigate excessive vegetative growth, reducing fruit drop and yield reduction. MC also redirects photo-assimilates toward reproductive growth, increasing sympodial branches and bolls per plant, ultimately improving lint yield and fibre quality. Cyclanilide enhances MC's efficacy by inducing enzymes that convert inactive GA20 to active GA1, further inhibiting gibberellin production (25).

Impact of cotton varieties on yield and related traits

The number of bolls per plant is a critical yield-contributing trait in cotton and its variation among different varieties can be attributed to their genetic potential and the availability of resources such as nutrients, water and light (26). Differences in seed cotton yield among genotypes likely reflect their yield-attributing characteristics, such as the number of matured open bolls and boll weight. Previous studies have shown that increased numbers of sympodia and bolls are often the result of better assimilation and efficient translocation of photosynthates to the reproductive organs, enhancing overall yield potential (27,28). For instance, these compact genotypes were resistant to bollworm attacks and produced healthy, mature bolls with greater boll weight, leading to higher yields. Moreover, individual plants have more opportunities to achieve maximum productivity when provided with optimum space, resulting in better nourishment and higher seed cotton yield per plant. However, wider spacing leads to higher yield components per plant, often offset by the increased plant population per unit area in closer spacing, resulting in higher yields.

Effects of crop geometry on cotton yield

Cotton yield is determined by bolls per unit area, boll weight, and lint percentage, which depend on genetics and boll weight influenced by genetics and environment. Suraksha variety showed higher yields due to superior growth and assimilate partitioning. Higher plant density reduced yield, while broader spacing increased boll weight and yield stability due to optimized microclimate and reduced competition (29). Studies consistently show that wider spacing leads to heavier bolls, more fruit branches, and increased photosynthate assimilation and translocation, resulting in better growth and higher yield (30). Wider spacing also promotes taller plants, more leaves and sympodial branches, contributing to higher productivity (31). Overall, optimizing plant spacing is crucial for maximizing cotton yield.

Impact of mepiquat chloride on seed cotton yield

Increasing plant density decreased boll weight and number, but MC application significantly improved boll number, seed cotton yield and boll weight. The highest yields (2345 kg/ha) were achieved with MC and cyclanilide at 400 ppm, which enhanced MC efficacy by inhibiting gibberellin production. MC promotes compact plant structure, mitigates intra-plant competition and regulates vegetative and reproductive growth, ensuring resources support boll formation (32). MC application restricts vegetative growth, promotes reproductive development, and improves light penetration, increasing boll weight, lint percentage, lint yield, seed cotton yield and seed index (33). MC also optimizes source-sink relationships, efficiently translocating photo-assimilates to reproductive structures, enhancing boll number and quality and improving lint yield and fiber quality (34).

Interpretation of Pearson Correlation Analysis of growth variables along with correlation matrix and heatmap

The study explores the genotypic correlations between plant traits, including plant height, sympodial branches, monopodial branches, sympodial length, total biomass, and internodal distance (Table 5 and Fig. 1). Plant height had a positive and significant correlation with sympodial branches (0.256*) but only a positive, non-significant correlation with monopodial branches (0.105 NS) and sympodial length (0.087 NS). Conversely, plant height showed a significant and negative correlation with total biomass (-0.253*) and a negative but non-significant correlation with internodal distance (-0.01 NS). Regarding the sympodial trait, the genotypic correlation was positive and non-significant for sympodial length (0.142 NS) and monopodia (0.047 NS), but it exhibited a significant and negative correlation with internodal distance (-0.306**).

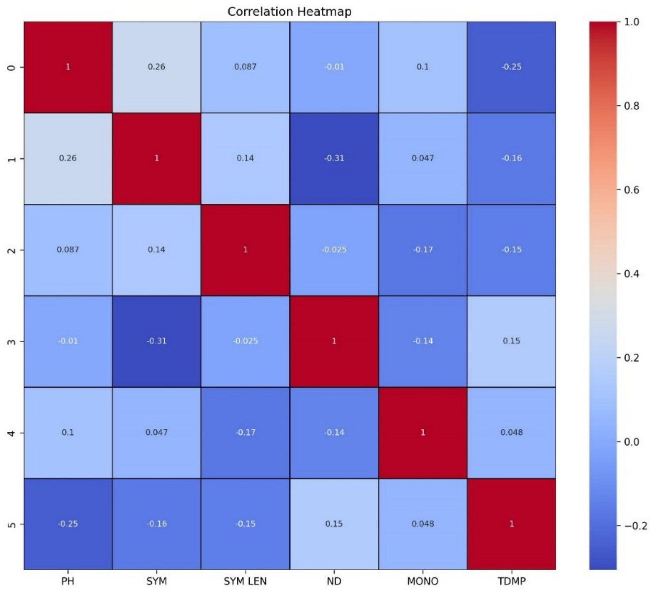

Fig. 1. Interpretation of Pearson Correlation Analysis of growth variables along with correlation matrix and heatmap

Table 5. Correlation analysis between growth parameters

Variables	Plant height	No. of sympodia	Sympodial length	Internodal distance	No. of monopodia	Total biomass
Plant height	1.0 **	0.256 *	0.087 NS	-0.01 NS	0.105 NS	-0.253 *
No. of sympodia	0.256 *	1.0 **	0.142 NS	-0.306 **	0.047 NS	-0.164 NS
Sympodial length	0.087 NS	0.142 NS	1.0 **	-0.025 NS	-0.171 NS	-0.15 NS
Internodal distance	-0.01 NS	-0.306 **	-0.025 NS	1.0 **	-0.135 NS	0.155 NS
No. of monopodia	0.105 NS	0.047 NS	-0.171 NS	-0.135 NS	1.0 **	0.048 NS
Total biomass	-0.253 *	-0.164 NS	-0.15 NS	0.155 NS	0.048 NS	1.0 **

A negative, non-significant correlation was also observed for total biomass (-0.164 NS). Sympodial length showed a positive, non-significant correlation with sympodia (0.142 NS). In comparison, plant height had a non-significant and negative association with monopodia (-0.171 NS), total biomass (-0.15 NS) and internodal distance (-0.025 NS). Internodal distance had a positive, non-significant correlation with total biomass (0.155 NS) but a significant and negative correlation with sympodia (-0.306**). Additionally, negative but non-significant correlations were noted between internodal distance and monopodia (-0.135 NS) and sympodial length (-0.025 NS). The monopodia trait showed a positive, non-significant correlation with both total biomass (0.048 NS) and sympodia (0.047 NS) but a non-significant, negative association with sympodia length (-0.171 NS) and internodal distance (-0.135 NS). Finally, the total biomass trait was positively and non-significantly correlated with internodal distance (0.155 NS) and monopodia (0.048 NS). At the same time, plant height showed non-significant, negative associations with sympodia (-0.164 NS) and sympodia length (-0.15 NS).

Interpretation of Pearson Correlation Analysis of yield attributes along with correlation matrix and heatmap

The study examined the genotypic correlations among various traits related to cotton yield, including boll/m², lint yield, seed cotton yield, harvest index, biological yield, boll weight, harvesting boll % (HBP) and stalk weight (Table 6 and Fig. 2). The findings revealed that boll/m² had a positive and significant correlation with lint yield (0.643**), seed cotton yield (0.608**), harvest index (0.321**), and biological yield (0.236*). However, boll/m² exhibited a significant and negative correlation with HBP (-0.711**) and boll weight (-0.262*) and a non-significant negative correlation with stalk weight (-0.055 NS). The study further demonstrated that boll weight had a positive and significant association with the harvest index (0.65**), seed cotton yield (0.6**) and lint yield (0.496**) while also showing a positive but non-significant correlation with HBP (0.221 NS). In contrast, boll weight significantly and negatively correlated with stalk weight (-0.517**) and biological yield (-0.285*). HBP showed a positive but non-significant correlation with boll weight (0.221 NS) but had a significant and negative correlation with lint yield (-0.442**), seed cotton yield (-0.416**) and biological yield (-0.284*). Although HBP negatively correlated with harvest index (-0.139 NS) and stalk weight (-0.071 NS), these were not statistically significant. Seed cotton yield was positively and significantly correlated with lint yield (0.94**), harvest index (0.787**) and boll weight (0.6**) but exhibited a significant and negative correlation with stalk weight (-0.45**) and HBP (-0.416**) and a non-significant negative correlation with biological yield (-0.015 NS). The study also found that stalk weight was positively and significantly associated with biological yield (0.899**). Still, it was significantly and negatively correlated with harvest index (-0.901**), boll weight (-0.517**), seed cotton yield (-0.45**) and lint yield (-0.394**). There was also a non-significant negative correlation with HBP (-0.071 NS). Finally, lint yield showed a positive and significant relationship with seed cotton yield (0.94**), harvest index (0.718**) and boll weight (0.496**), along with a positive but non-significant correlation with biological yield (0.018 NS). However, lint yield was significantly and negatively correlated with HBP (-0.442**) and stalk weight (-0.394**). The harvest index was positively and significantly associated with seed cotton yield (0.787**), lint yield (0.718**) and boll weight (0.65**) but negatively and significantly correlated with stalk weight (-0.901**) and biological yield (-0.624**). A negative but non-significant correlation with HBP (-0.139 NS) was also observed.

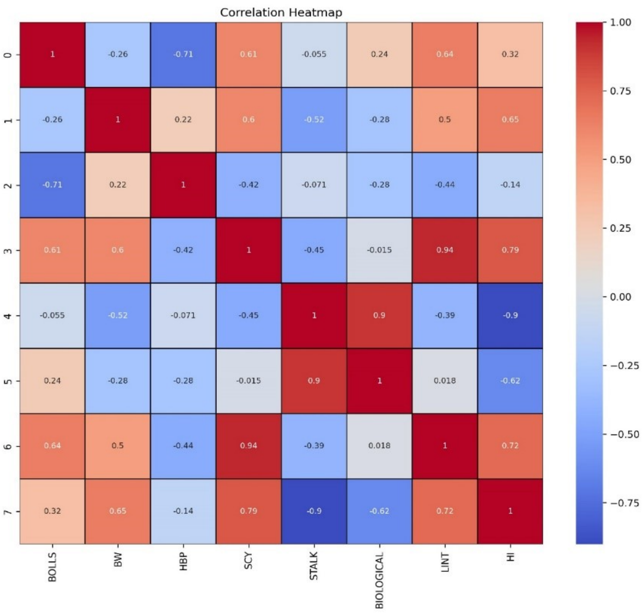

Fig. 2. Interpretation of Pearson Correlation Analysis of yield attributes along with correlation matrix and heatmap

Table 6. Correlation analysis between yields attribute

Variables	Bolls/m²	Boll weight	Harvestable boll %	Seed cotton yield	Stalk yield	Biological yield	Lint yield	Harvest index
Bolls/m²	1.0 **	-0.262 *	-0.711 **	0.608 **	-0.055 NS	0.236 *	0.643 **	0.321 **
Boll weight	-0.262 *	1.0 **	0.221 NS	0.6 **	-0.517 **	-0.285 *	0.496 **	0.65 **
Harvestable boll %	-0.711 **	0.221 NS	1.0 **	-0.416 **	-0.071 NS	-0.284 *	-0.442 **	-0.139 NS
Seed cotton yield	0.608 **	0.6 **	-0.416 **	1.0 **	-0.45 **	-0.015 NS	0.94 **	0.787 **
Stalk yield	-0.055 NS	-0.517 **	-0.071 NS	-0.45 **	1.0 **	0.899 **	-0.394 **	-0.901 **
Biological yield	0.236 *	-0.285 *	-0.284 *	-0.015 NS	0.899 **	1.0 **	0.018 NS	-0.624 **
Lint yield	0.643 **	0.496 **	-0.442 **	0.94 **	-0.394 **	0.018 NS	1.0 **	0.718 **
Harvest index	0.321 **	0.65 **	-0.139 NS	0.787 **	-0.901 **	-0.624 **	0.718 **	1.0 **

Conclusion

From this study, it was concluded that out of the three varieties tested for plant growth and dry matter accumulation in the fruiting body of the Suraksha variety, the seed cotton yield is affected. Comparing the spacing patterns in the study, the 90 x 15 cm spacing produced a higher number of fruiting structures and more sympodial branches, with an acceptable plant structure suitable for mechanical harvesting. Concerning the plant growth regulators of the study, mepiquat chloride and cyclanilide at 400 ppm contributed toward reducing the foliage's size, enhancing the growth of the fruiting body and compactness of plant habit readily amenable to mechanical harvesting. Hence, the Suraksha variety sown at 90 x 15 cm and treated with mepiquat chloride and cyclanilide @ 400 ppm provided compactness with appropriate plant height, more number of sympodial branches and optimum sympodial length to achieve the highest seed cotton yield than other varieties and efficient for mechanical harvest.

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Authors' contributions

Dhamodharan P conducted the experiment, recorded data, and performed data analysis. Somasundaram S supervised the experiment, formulated the experimental design, provided assistance and contributed to manuscript corrections and data analysis. Thirukumaran K, Kavitha R, Ravichandran V and Anantharaju P offered guidance on experimenting with and correcting the manuscript. All authors reviewed and approved the final version of the manuscript.

Compliance with ethical standards

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

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

While preparing this work, the author used ChatGPT to improve language and readability. After using ChatGPT, the author reviewed and edited the content as needed and takes full responsibility for the publication's content.

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