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RESEARCH ARTICLE

Relationship and dissection of compact plant architecture traits amenable for mechanical harvesting in cotton

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Abstract

The need for mechanical harvesting in cotton production has become paramount as labor costs continue to rise. Efficient machine harvesting requires short and compact cotton plants. This study developed ten F_1 populations by crossing five Indian-origin cotton genotypes using a half -diallel mating design. Field trials were conducted in two seasons, *Kharif* 2022 and summer 2023, at Coimbatore, India. Significant genetic variability was observed across all plant architecture traits, with strong G × E interactions ($P \leq 0.01$), highlighting clear opportunities for breeding compact high-yielding cotton types. A consistent negative correlation between plant height and seed cotton yield in both environments suggested that shorter plants provided greater yield stability. An ideal plant height of 75-110 cm was identified as the most suitable for mechanized harvesting. Within this ideal range, architecture traits such as zero monopodia, internode and branch lengths showed a consistent negative association with yield, while plant density, sympodial branch origin and number were positively linked to higher yield. Stepwise regression identified the groups of mainstem internode (1^{st}-4^{th} nodes) and sympodial branch lengths (lower, middle, upper) as key yield-influencing traits, offering targets for breeding compact, high-performing cotton types. Pooled values indicated an ideal mean mainstem internodes lengths (MIL) of approximately 5.2 cm and sympodial branches lengths (SBL) of approximately 19.9 cm, with shorter internodes enhancing plant sturdiness and uniformity, while reduced sympodial length improved canopy openness, light penetration and harvest efficiency with minimal trash intake. The findings provide practical recommendations on compact plant architecture traits, particularly ideal internode and branch lengths, to enhance yield potential and facilitate mechanical harvesting in cotton.

Keywords: compact traits; correlation; cotton; internode length; regression; sympodia; yield

Introduction

Plant architecture, defined as the spatial arrangement of above-ground plant components, plays a crucial role in influencing light interception, radiation-use efficiency, growth, biomass production, resource partitioning and yield potential (1). Plant architecture significantly influences agricultural practices, particularly in cotton production, where studies have emphasized its critical role in crop management (2, 3). Understanding and manipulating plant architecture is vital for optimizing crop management. In the case of cotton, shorter plant genotypes are favored for machine harvesting, primarily due to the challenges posed by excessive vegetative growth and delayed maturity in taller plants (2, 4). Several key factors, such as shorter plant height, uniformity, shorter sympodial branch length, the lack of monopodial branches (zero monopodia), synchronized flowering and consistent boll bursting, all contribute to an ideal compact plant canopy suitable for mechanical harvesting and high-density row planting (2, 3, 5).

Cotton-growing regions globally emphasize optimum plant height, with less than 120 cm for spindle-pickers and less than 80 cm for stripper-pickers. These recommendations are rooted in practical field experiences and have a direct influence on the efficiency and performance of mechanical cotton harvesting equipment (2, 3, 6). The height of the first sympodial branch origin from the ground of over 20 cm minimizes defoliant intake and aids cotton picker efficiency (2, 7). Additionally, attributes such as mainstem internode length (height-to-node ratio) and sympodial branch length are associated with both positive and negative effects on harvest efficiency and yield. Shorter internodes and moderate branch lengths are generally associated with improved harvest efficiency, whereas excessive elongation or overly long branches are often linked to yield reduction. These observations highlight the benefits of promoting compact plant architecture (2, 3, 8, 9).

However, it's important to note that within the specific height range of 75 to less than 110 cm, limited information is available regarding the effects of detailed architectural attributes such as internode and fruiting branch lengths on cotton yield. Environmental factors, including rainfall and temperature, exert a significant influence on cotton plant architecture. Drought conditions tend to reduce plant height and the number of nodes (10, 11). The considerable variations in plant architecture among different cotton genotypes are well-documented (12). Yet, our understanding of how weather conditions, cultivars, plant density and agronomic management practices interact with cotton plant architecture and its ultimate influence on yield remains limited (13, 14). In India, labor shortages and high costs make mechanical harvesting essential (15). Despite labor shortages, 95 % of cultivated cotton hybrids in India are Bt hybrids, necessitating three pickings due to unsynchronized boll openings. The Bt hybrids have a long growth cycle (150-160 days) and grow up to 1.5 m tall. They have monopodial branches with fewer bolls on fruiting branches and extended boll opening periods, making them unsuitable for mechanical harvesting.

Achieving the desired plant architecture for mechanical harvesting requires combining favorable genetic traits from diverse genotypes. In this study, Indian-origin cotton varieties were crossed using a half-diallel design to evaluate the inheritance of key biometric traits (2). This approach enabled the identification of superior cross combinations that can produce compact, early maturing and high-yielding hybrids suitable for mechanized harvesting (2). The use of a half-diallel design in this study is supported by high variability and identified superior combiners among five genotypes across two environments (2). Non-additive gene action predominated, with specific combining ability (SCA) variances exceeding general combining ability (GCA) variances and both additive and dominant genes influenced traits, with dominance being stronger. The selected genotypes, chosen for their proven variability and high performance, provided a robust basis for evaluating combining ability.

In addition, this study evaluated key plant architecture and seed cotton yield traits to optimize cotton for high-density planting and efficient mechanized harvesting in India. Specifically, (i) examined essential plant architecture traits within the optimal height range of 75 to less than 110 cm to assess their impact on yield, (ii) identified major yield-influencing traits via stepwise regression and (iii) provided practical guidance for selecting compact, high-performing plants suited to mechanized harvesting.

Materials and Methods

Experimental location and material generation

The five cotton genotypes, namely TVH-007, Suraksha, CO-17, Nano and NDLH-1938 were selected as parents for the experiment based on their compact, semi-compact and robust plant types. The hybridization process used the half-diallel method, resulting in the creation of 10 F1 hybrids (single crosses) in summer 2022 (Fig. 1A). The experiments were conducted in the Department of Cotton, Centre for Plant Breeding and Genetics, Tamil Nadu Agricultural University (TNAU), Coimbatore, following a randomized complete block design with three replicates. Each genotype was cultivated on 18 m long ridges, arranged in eight rows with precise spacing of 90 cm (row × row) and 30 cm (plant × plant). This method adhered to the recommended agronomic practices outlined in the TNAU crop production guide, ensuring optimal plant growth conditions.

Evaluation and data collection

Data were collected from two field experiments conducted in Coimbatore city: E1 - *Kharif* 2022 (11.0122° N, 76.9354° E and 432.0 m elevation) and E2 - summer 2023 (11.0122° N, 76.9354° E and 430.9 m elevation). The monthly weather report includes average precipitation, air temperature and sunshine duration during the crop growing seasons are presented in (Fig. 1B). At harvest, pre-marked and randomly tagged five plants per row were used for measuring plant height (PH), mainstem internodes lengths (MIL) and sympodial branches lengths (SBL). Plant height was measured from the cotyledonary node to the shoot apex. The MIL and SBL were categorized into groups (3). The MIL was divided into four groups: the 1st group included the nodes from the bottom up to the squaring stage (usually 1st–7th node); the remaining part was evenly divided into the 2nd (8th– 12th node), 3rd (13th– 17th node) and 4th (>17th node) groups. Similarly, the SBL was grouped into three: the lower sympodial branches (LSB, 1st–5th branch), middle sympodial branches (MSB, 6th–10th branch) and upper-sympodial branches (USB, >10th branch). The number of plants per square meter (PD), height of the first sympodial branch origin (FSB, cm) and number of monopodia (NMB), sympodial branches (NSB) and boll per plant (BP) were measured in both experiments. Seed cotton yield (SCY) was determined by hand-picking plants from the inner rows of each plot. The evaluation method for compact plant architecture and yield traits amenable to mechanical harvesting in cotton is depicted in Fig. 2.

Testing mechanical cotton harvesting

The compact genotypes, alongside the standard checks KC3 (robust or more vegetative plant type), DCH-32 (robust plant type) and Suraj (semi-compact plant type), were evaluated. These diverse plant architecture traits were subjected to mechanical harvesting at the Department of Cotton, TNAU, Coimbatore, India. The evaluations were conducted using the newly designed Shaktiman Cotton Spindle Picker (Cotton Master 1437, Shaktiman®, Rajkot, Gujarat, India) during both seasons.

Statistical analysis

Statistical analysis was performed to assess the data collected from the genotypes. Analysis of variance (ANOVA) was performed, followed by Tukey's honestly significance difference (HSD) test, implemented through the "agricolae" R-package (v.4.2.3), to identify significant differences among the pooled trait means at $p \leq 0.05$ (16). The Bartlett's test was carried out test the homogeneity of error-

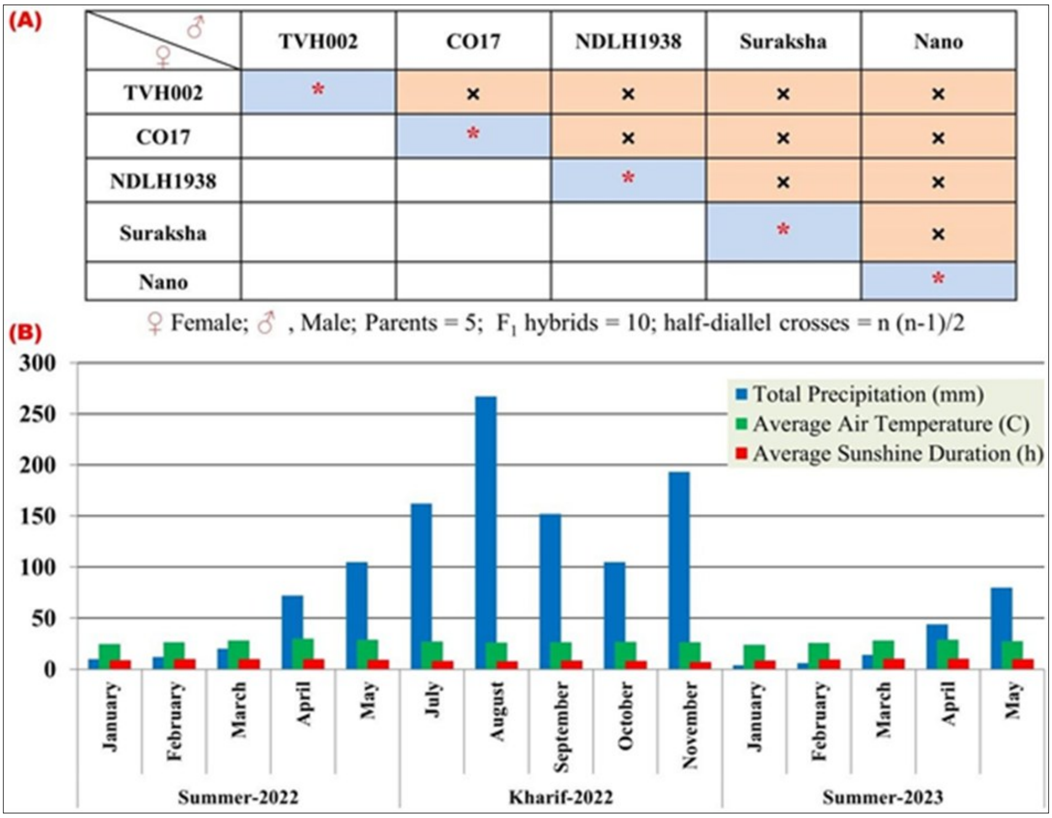

Fig. 1. (A) The half-diallel crossing plan. × = direct crosses; * = parents (selfings). (B) Weather data for Coimbatore's 2022-23 cotton growing season.

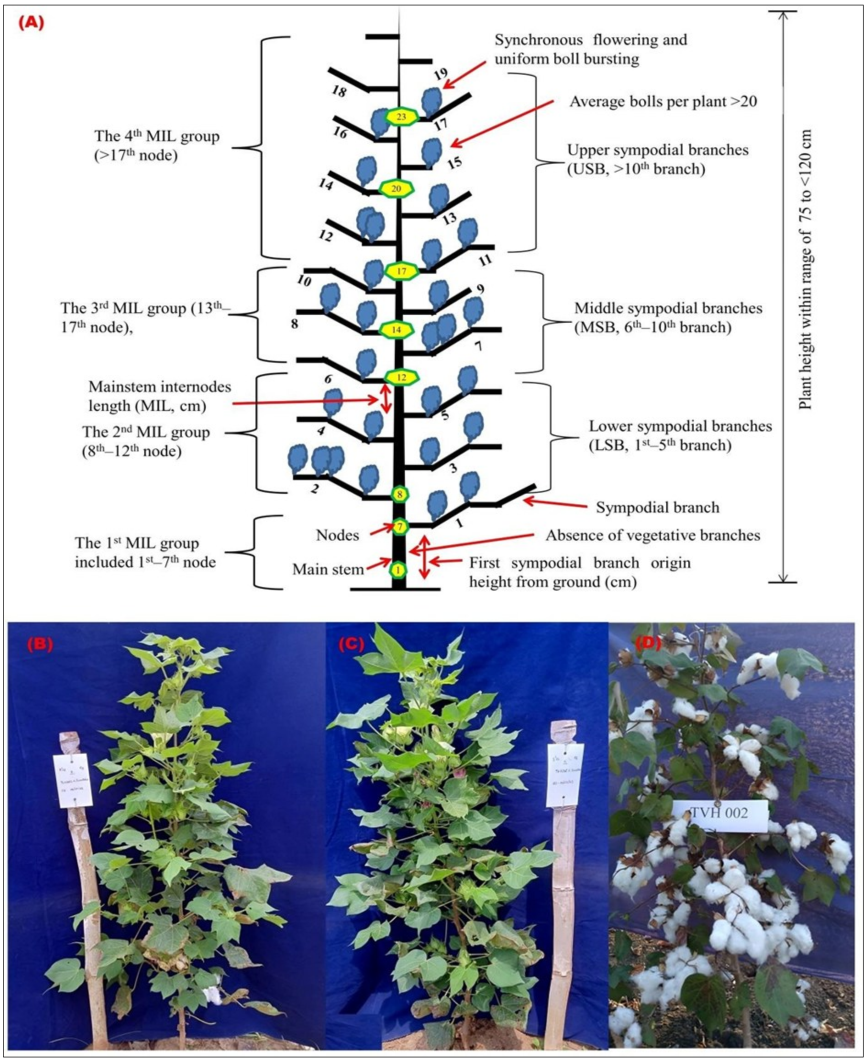

Fig. 2. A) Method of traits evaluation and desired compact plant architecture traits amenable for mechanical harvesting using cotton spindle picker. B & C) Field view of a single compact plant of cross TVH002 × Suraksha in E1 and E2, respectively. D) Filed view of zero monopodial compact cotton culture TVH002 plant.

variances across locations using the "bartlett.test" R-package (17). Correlation analysis was conducted using the "corrplot" R-package to explore the association between plant height, other architectural traits and yield (18). Stepwise regression analysis was carried out with the "leaps" R-package to investigate the factors influencing architectural traits on seed cotton yield, with entry and stay criteria set at a significance level of 0.05 (19). Box-and-whisker plots were generated for all traits and scatter plots were prepared to illustrate relationships between seed cotton yield and architectural attributes using Microsoft Excel (Microsoft Corp., Redmond, WA, USA).

Results and Discussion

Pooled mean squares of RCBD-ANOVA

The pooled ANOVA mean squares revealed statistically significant differences among genotypes ($p \leq 0.01$), reflecting sufficient trait variability. Genotypic variability accounted for the largest portion of this variability (Table 1). These findings imply that genotypes have enough potential for improved selection outcomes in the future breeding programmes (20). The environment also significantly influenced most compact plant traits, except for lower sympodial branches and bolls per plant. These findings align with previous reports, when evaluating cotton genotypes in diverse environments for adaptation and stability (21). Notably, the genotypes × environment interaction (GEI) exhibited varying mean squares among studied traits, ranging from 0.08 for number of monopodial branches to 22878.01 for seed cotton yield, with the lowest GEI observed in the MIL group. The impact of genotypic variation on plant height and seed cotton yields outweighed GEI and environmental effects. Both PH and SCY variations were primarily influenced by genotypes, with minor contributions from GEI and the environment. These results are consistent with previously reported GEIs in cotton (2, 22, 23). It was observed that error variances across locations were homogeneous for studied traits. Bartlett's X^2 (chi-squared) values are given in Table 1. To provide a comprehensive understanding of the results, the pooled means ($p \leq 0.05$), standard-errors (SE±m), coefficients of variation (CV %) and HSD values are given in Table 2. Additionally, for enhanced clarity, individual means for experiments E1 and E2 are depicted using boxplots and scatterplots (Supplementary Fig. S1 & S2).

Correlation analysis

Correlation analysis was used to assess trait relationships due to its simplicity and interpretability. The impact of cotton plant height on seed cotton yield potential is complex (Fig. 3). Taller plants have more sympodial branches and fruit bearing sites, which enhances yield (24, 25). However, vigorous/robust vegetative growth could result in problems such as closed plant canopy, increased boll/fruit rot and boll loss. Nevertheless, taller plants may compensate with better growth in the upper canopy in situations of severe fruit loss in the lower and/or middle canopy. The correlation between plant height and seed cotton yield varies considerably in the literature, with some studies reporting a negative association, while others have found a positive association and still others have reported no correlation at all (2, 3, 9, 24, 26-33). These inconsistencies may arise from differences in genetic backgrounds and production systems; in particular, compact plant types suited for high-density planting and mechanical harvesting often require optimized plant height to balance yield potential with harvest efficiency.

Collecting data from diverse seasons or environmental conditions within the same region can provide valuable insights into complex relationships. In this study, plant height ranged from 75 to less than 110 cm in individual experiments. When combining two field experiments, the range narrowed to 80-101 cm. This range is considered suitable for mechanical harvesting (2, 3, 6, 7). The mean height and other architectural traits values varied depending on genotypes (Table 2). The average plant height was 90.15 cm and a highly significant ($p \leq 0.01$) negative correlation with seed cotton yield (1415.04 kg/ha) was observed in both environments, with r = -0.33 in E1 and r = -0.72 in E2 (Fig. 3A & 3B). E2 exhibited a weaker negative correlation than E1, suggesting that shorter plants with a narrower height range may enhance boll retention (mean bolls per plant = 21.63) and contribute to more stable yields (Supplementary Fig. 1 & 2). This can be attributed to a significant decrease in rainfall and an extended period of sunny weather from January to March in E2-2023 (Fig. 1B).

Table 1. Pooled mean squares for RCBD-ANOVA of plant architecture and yield traits

Traits	Environment (E)	Replication within the (E)	Genotype (G)	G× E	Pooled error	Bartlett's-K-squared
	(Df = 1)	(Df = 1)	(Df = 1)	(Df = 1)	(Df = 1)	(Total = 107)
PD (Sq.m)	0.51**	15.69	25.11**	0.63**	0.65	1.86
PH (cm)	132.97**	6.57	208.59**	13.40**	5.21	1.32
NMB (nos.)	0.24**	0.04	0.60**	0.08ns	0.02	1.86
FSB (cm)	5.89**	0.59	39.56**	1.67**	1.35	0.29
NSB (nos.)	11.47**	4.79	17.17**	3.28**	2.44	0.09
LSB (cm)	0.29ns	7.82	83.74**	2.37**	2.85	2.31
MSB (cm)	10.76**	2.74	53.06**	3.96**	2.46	1.96
USB (cm)	4.71**	16.78	29.33**	4.22**	1.53	2.06
MIL (1-7, cm)	0.32**	0.10	0.46**	0.15**	0.03	0.71
MIL (8-12, cm)	0.87**	0.04	0.93**	0.31**	0.05	0.69
MIL (13-17, cm)	0.38**	1.33	0.40**	0.16ns	0.06	0.73
MIL (>17, cm)	0.15**	0.61	0.72**	0.15**	0.04	0.66
BP (nos.)	0.05ns	4.21	16.12**	7.33**	1.89	0.07
SCY (kg/ha)	10250.37**	1546.81	73794.03**	22878.01**	836.87	27.39

** Non-significant and Significant differences at $p \leq 0.01$, respectively. PD: plant density; PH: plant height; NMB: number of monopodial branches; FSB: height of first sympodial branch origin; NSB: number of sympodial branches; LSB: lower sympodial branches length; MSB: middle sympodial branches length. USB: upper sympodial branches length; MIL: mainstem internodes length groups 1 to >17; BP: bolls per-plant; SCY: seed cotton yield.

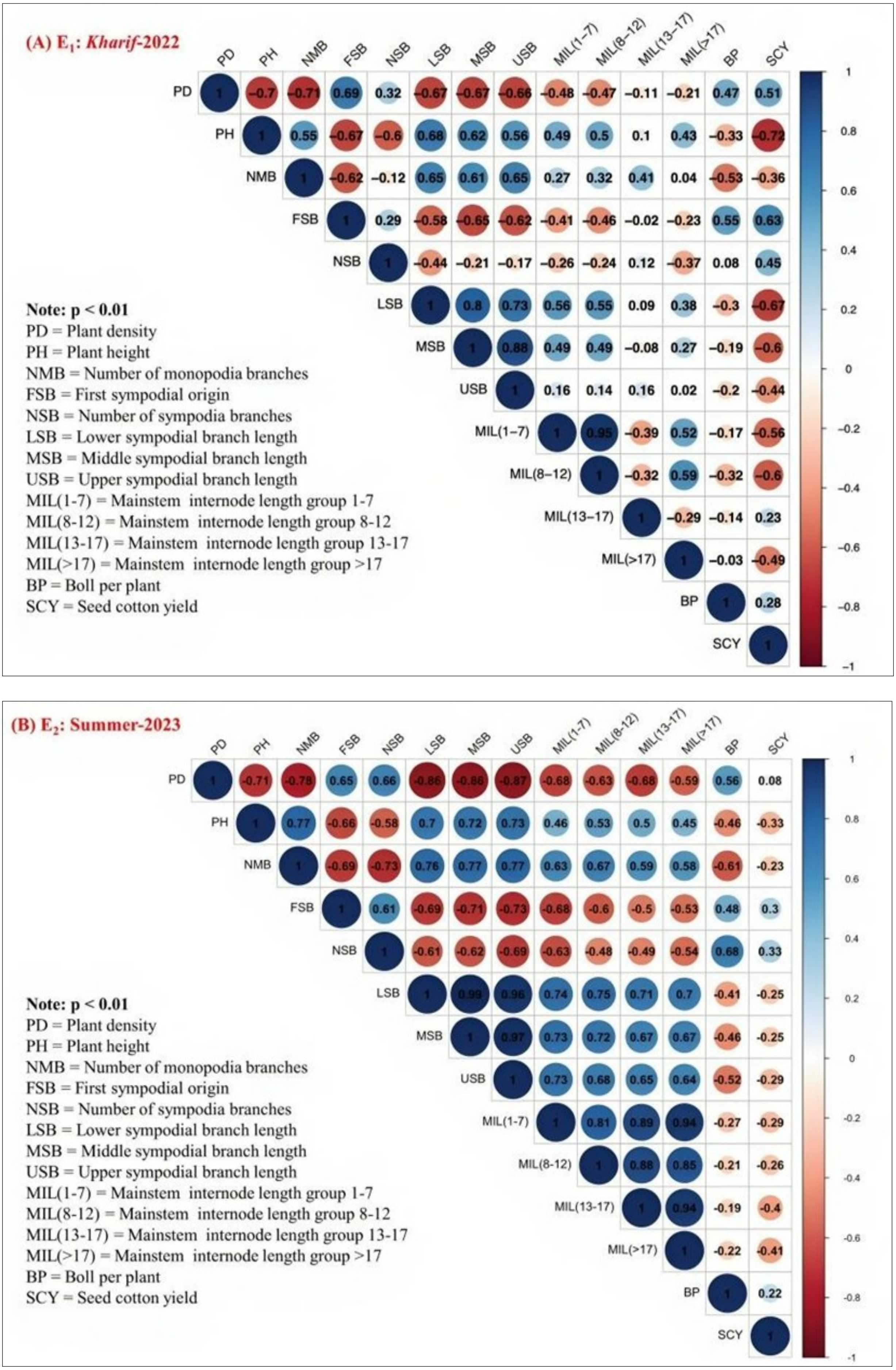

Fig. 3. A & B. Correlation matrixes. Correlation coefficients (*r*) between traits were calculated using Spearman's method in 'R'. The range of numbers (-1 to 1) represents the Spearman's rank between traits on the vertical and horizontal axes. Circle size and colour in matrix reflect the correlation strength between traits.

Table 2. Combined mean-performance of cotton-genotypes for plant architecture and yield traits

Entries	PD	PH	NMB	FSB	NSB	LSB	MSB	USB	MIL (1-7)	MIL (8-12)	MIL (13-17)	MIL (>17)	BP	SCY
TVH-002	10.82a-d	84.00h-j	0.46f	22.56b-e	19.61a-d	23.22c-g	21.75d-g	17.08d-g	3.60ab	6.53ab	6.40ab	5.71ab	21.73a-e	1333.34ef
CO-17	11.16a-c	92.16c-f	0.83a-f	23.14b-d	18.30c-e	21.92e-h	21.79d-g	18.10b-f	3.56ab	6.57ab	6.39ab	5.65ab	22.03a-e	1288.20f
NDLH-1938	7.27gh	101.00ab	1.20ab	17.99hi	16.33e	31.71a	29.95a	22.43a	3.93a	7.00ab	6.70ab	6.03a	18.33ef	1172.50g
Suraksha	7.01gh	97.98a-c	1.23a-c	19.57ghi	17.89de	30.05a	27.34ab	21.06a-c	3.97a	7.06a	6.87a	6.05a	25.57a	1407.79de
Nano	8.60e-g	87.33f-i	1.00a-e	19.84f-h	18.67c-e	25.56b-d	25.62bc	19.13a-d	3.70ab	6.80ab	6.53ab	5.79ab	19.67c-f	1292.79f
TVH-002 × C-017	12.50a	81.66ij	0.50f	24.45a-c	21.94ab	20.29gh	20.20fg	13.62g	3.50ab	6.40ab	6.34ab	5.63ab	25.62a	1188.54g
TVH002 × NDLH1938	10.81a-d	81.00ij	0.90a-f	22.97b-e	19.25b-e	21.33f-h	21.15e-g	15.05e-g	3.46ab	6.61ab	6.20ab	5.53ab	21.90a-e	1568.87ab
TVH-002 × Suraksha	9.34d-f	93.50b-f	0.77b-f	21.81d-f	21.37a-c	22.45d-h	23.26c-f	17.86b-f	3.32b	6.48ab	6.13b	5.36b	21.39b-e	1506.85bc
TVH-002 × Nano	11.34a-c	80.00j	0.66d-f	25.82a	22.77a	20.85gh	19.56g	14.45fg	3.66ab	6.75ab	6.51ab	5.81ab	22.65a-d	1617.44a
CO-17 × NDLH-1938	10.49cd	92.33c-f	0.71c-f	22.72b-e	19.54a-e	22.88c-g	23.08c-f	17.09d-g	3.53ab	6.86ab	6.50ab	5.78ab	22.50a-d	1282.56f
CO-17 × Suraksha	10.23c-e	91.00d-g	0.67d-f	23.81a-d	19.02b-e	21.16f-h	20.50fg	14.51fg	3.50ab	6.63ab	6.47ab	5.70ab	23.13a-c	1423.06cd
CO-17 × Nano	12.48ab	89.66e-h	0.60ef	20.68e-g	19.77a-d	18.99h	20.49fg	14.50fg	3.49ab	6.38b	6.07b	5.51ab	24.00ab	1629.32a
NDLH1938 × Suraksha	7.19gh	100.00ab	1.16a-c	23.22b-d	18.98b-e	26.25bc	25.03b-d	19.28a-d	3.53ab	6.63ab	6.50ab	5.70ab	18.96d-f	1430.37cd
NDLH-1938 × Nano	10.79b-d	96.00a-e	1.10a-d	22.09c-f	18.89b-e	23.79c-g	21.84d-g	17.61c-f	3.50ab	6.66ab	6.30ab	5.62ab	20.97b-e	1319.20f
Suraksha × Nano	8.03f-h	85.10g-j	0.63d-f	24.92ab	18.04de	25.12b-e	22.95c-f	18.58b-e	3.53ab	6.45ab	6.28ab	5.55ab	21.96a-e	1608.77a
KC3 (SC1)	6.42h	98.16a-c	1.30a	18.28g-i	17.05de	28.22ab	25.46bc	21.50ab	3.90a	6.73ab	6.61ab	5.97ab	16.66f	1332.23ef
Suraj (SC2)	7.51gh	94.33a-e	1.03a-e	19.09g-i	21.50a-c	30.66a	29.48a	22.43a	3.83ab	7.02ab	6.64ab	5.93ab	22.96a-d	1463.71cd
DCH32 (SC3)	6.76h	97.33a-d	1.10a-d	16.95i	18.33c-e	24.62c-f	23.82c-e	19.03a-d	3.8ab	6.95ab	6.68ab	5.81ab	19.70c-f	1429.83cd
Mean	9.37	90.15	0.92	21.65	19.29	24.39	23.46	17.77	3.69	6.61	6.51	5.70	21.63	1415.04
SE±m	1.69	3.71	0.26	2.43	3.27	3.53	3.28	2.01	0.28	0.37	0.40	0.34	2.24	47.13
CV (%)	8.64	2.5	17.23	5.37	8.10	6.93	6.69	6.97	4.78	3.51	3.77	3.74	6.37	2.04
HSD (0.05)	2.16	1.99	0.43	2.40	2.17	4.10	2.86	2.02	0.42	0.53	0.33	0.40	1.89	109.80

No-significant differences ($p \le 0.05$, Tukey's-HSD test) among means with the same letter (A-l) in each-column.

The range of plant densities observed varied, ranging from 6.42 in KC3 to 12.50 plants m^{-2} in TVH002 × C017, with an average value of 9.37 plants m^{-2}. This study indicates that these densities can accommodate a higher number of plants per unit area, it suggests that the studied genotypes were suitable for high-density cotton planting system with a recommended spacing of 90/60 (rows) × 30/15/10 cm (plants) (5). All genotypes showed a highly significant ($p \leq 0.01$) negative correlation between plant height and plant density in both environments (r = -0.70 in E1; r = -0.71 in E2), while plant density exhibited a moderate and significant positive correlation with seed cotton yield in E1 (r = 0.51**), but weak correlation in E2 with r = 0.08* (Fig. 3A, B; Supplementary Fig. S2). Compared to higher plant densities, the positive correlation between plant density and seed cotton yield decreased, while it increased with plant height. The mean number of monopodial branches was 0.95, ranging from 0.46 in TVH002 to 1.30 in KC3 and showed a significant negative correlation with yield (r = -0.36* in E1 and r = -0.23* in E2). This study suggests that excessive vegetative growth can lead to boll loss, directly impacting yield. This also suggests that an increase in monopodia causes a reduction in yield and an increase in plant robustness poses a variety of challenges in cultural practices for cotton cultivation (3-7).

A significant positive correlation was observed between the height of first sympodial branch origin and seed cotton yield, with r = 0.63** in E1 and r = 0.30* in E2, indicating that a higher position of the first sympodial branch may contribute to improved yield performance by promoting better canopy structure and efficient resource utilization. The average height of the first sympodial branch origin was 21.65 cm, an optimal height that minimizes residual defoliant or trash intake along with the harvested produce in the harvester cabin and is best suited for stripper cotton pickers (2, 3, 7). This study focused on identifying suitable genotypes possessing optimal range of plant height (~120 cm) and first sympodial height from the ground at 15 cm or above, shorter sympodial branches and uniformity in bursting for mechanical harvesting. Earlier research suggested varying height preferences and recommended heights below 80 cm for stripper-pickers and below 120 cm for spindle-pickers (6, 7). Conversely, a few studies have indicated that plant heights of 80-120 cm are considered suitable for spindle pickers, whereas heights of 75-110 cm are more appropriate for stripper mechanical harvesters (2, 3). Through extensive testing of different genotypes at various plant heights in both seasons, the study found that a range of 75 to less than 110 cm is more appropriate for mechanical harvesting when employing a row-to-row spacing of 90 × 90 cm and with 30 cm between plants. In some situations, extreme environmental factors can cause plants to grow taller and robust, which may be managed by harvester adjustments, though such modifications are generally not recommended by technicians. The result was encouraging and had few drawbacks like trash accumulation and the designers are considering developing a separate motorized cleaner to remove the trash immediately after harvest.

This study also emphasizes the importance of the height of first sympodial branch origin from base of the ground and its suitability to machine harvesting. The height of first sympodial branch origin over 20 cm minimizes residual-defoliant intake and this height was best suited for spindle and stripper-pickers for picking cotton effectively with minimal trash accumulation (2, 3, 6, 7). The testing of mechanical harvester revealed the optimum height of 20 cm from ground level. Except the genotype NDLH1938 and three standard checks, other genotypes were found more suitable with ~20 cm height at which first sympodial branch originates from the base of the plant or ground level.

On the other hand, the number of sympodial branches exhibited a positive association with yield in both environments. This indicates that increased sympodial branches number results in more fruit bearing sites and enhances the plant's ability to compensate for a higher fruit yield. The average number of sympodial branches ranged from 16.33 in NDLH1938 to 22.77 in TVH002 × Nano, with an overall mean of 19.29. The length of sympodial branch groups and mainstem internodes length groups showed a significant negative correlation with yield and a positive correlation with plant height in E1 and E2. These results suggest that longer mainstem internodes and sympodial branch length contribute to robust and taller plants. However, such plant architecture poses several challenges in cotton agronomic practices, including increased lodging risk, difficulty in intercultural operations due to longer branches, reduced plant accommodation per unit area, higher incidence of sucking pests, poor light penetration within the canopy and a greater likelihood of premature boll drop, along with reduced suitability for mechanical harvesting (25). This study identified optimal trait lengths that contributed to increased plant compactness and stable yield across environments, a combination considered preferable for mechanized harvesting (2, 3).

Step wise regression analysis

Plant height influences canopy size, while mainstem internode length and sympodial branch length also impact the even distribution of canopy, sufficient light penetration and ultimately affect cotton yield (26). In this study, we investigated how these plant architecture traits influence seed cotton yield within a specific plant height range (75 to less than 110 cm) using stepwise regression analysis. Regarding sympodial branches, the average length of lower sympodial branch was 24.39 cm, slightly longer than that of the middle sympodial branch at 23.46 cm, while upper sympodial branch had an average length of 17.77 cm (Table 2; Supplementary Fig. 1). In terms of mainstem internode length (MIL), the mean length of internodes in the 1st MIL group (1-7) was the shortest at 3.69 cm. The internodes in the 2nd (8-12) and 3rd (13-17) groups were approximately twice as long as those in the first group, measuring 6.61 cm and 6.51 cm, respectively. The internode length in the 4th group was of medium length, averaging 5.70 cm.

Stepwise regression analysis revealed that in E1 (*Kharif* 2022), PD, PH, FSB length, LSB length, MSB length and the 1st, 2nd and 4th mainstem internode length groups significantly influenced seed cotton yield. When evaluated individually, their coefficients of determination (R^2) were 2.1 %, 5.17 %, 3.8 %, 16.2 %, 13.2 %, 5.63 %, 9.39 % and 0.11 %, respectively. The optimized model showed that these traits collectively explained 52 % (R^2) of yield variance (Table 3). These results indicate that higher PD, shorter PH and longer FSB length were beneficial for yield and suitable for mechanical harvesters. Such traits allow higher plant accommodation, maintain compact and uniform stands and enable smoother operation of harvesting machinery. A longer FSB further minimizes trash intake by preventing picker contact with the ground.

Longer LSB and MSB had a slight negative impact. Shorter internodes in the 1st mainstem group, longer internodes in the 2nd and intermediate length in 4th mainstem group may increase yield potential. This could be attributed to the shorter internode length in

Table 3. Regression models between plant architecture and yield traits in two seasons

Year/Season	Equation	R^2	Adjusted R^2	Residual SE
E1-*Kharif*-2022	Y = 2 972.30-29.71X1-3.07X2+33.56X3-53.31X4+43.24X5+1 218.04X6+463.85X7-1 558.07X8 Where, X1, Plant density; X2, Plant height; X3, height of first sympodial branch origin; X4 and X5, Lower and middle sympodial branches length; X6-X8, internodes length of 1st, 2nd and 4th groups.	0.52	0.41	70.01
E2-Summer-2023	Y = 2 904.93-8.19X1-6.05X2-2.65X3+58.83X4-92.36X5-28.85X6 Where, X1, Plant height; X2-X4, Lower, middle and upper sympodial branches length; X5-X7, internodes length of 1st, 2nd and 3rd groups.	0.67	0.55	61.38

the 1st group, which is often accompanied by the establishment of larger aerial roots during early crop growth stage, leading to improved water and nutrient uptake from soil (34, 35). Furthermore, the low mainstem internode length (1st group) value before squaring reflected the spring temperatures, which did not impose limitations on yield since the crucial leaves responsible for supplying assimilates to bolls were not yet fully developed or had premature bolls (36).

In E2 (summer 2023), PH, LSB length, MSB length, USB length and the 1st, 2nd and 3rd mainstem intermodal length groups were identified as significant factors for seed cotton yield. Individually, their R^2 values of 3.67 %, 10.2 %, 17.2 %, 5.10 %, 11.30 %, 3.9% and 0.08 %, respectively. The optimized regression model indicated that these seven traits accounted for 67 % (R^2) of yield variance (Table 3). Shorter PH and shorter lengths of LSB, MSB and USB enhanced light penetration to the crop base, promoting early boll retention and filling (37). Longer internodes in the 2nd and 3rd mainstem groups and shorter ones in the 1st group increased yield. The results suggested that elongation of the 2nd group's internodes during early squaring to early bloom, a period of rapid growth, led to more fruit sites and avoided premature senescence (2, 3, 34, 36). However, excessive elongation of internodes in the 3rd group during peak squaring to peak bloom could divert assimilates toward vegetative growth, leading to a reduction in yield (3, 38).

The combined findings of this study indicate that within the plant height range of 75 to less than 110 cm for mechanical harvesting, particular attention should be given to the internode length of the mainstem groups (MIL, 1st to 4th) and the length of the sympodial groups (LSB, MSB and USB). Optimal ranges for these architectural attributes have been identified as follows: 3.32 to 3.97 cm for MIL 1-7 (with shorter lengths being more favorable); 6.38 to 7.06 cm for MIL 8-12; 6.13 to 6.87 cm for MIL 13-17; 5.36 to 6.05 cm for MIL >17 (again, shorter lengths are preferred) and 8.99 to 31.71 cm for LSB, 19.56 to 29.95 cm for MSB and 13.62 to 22.43 cm for USB (where shorter lengths than the given range are optimal for compact sympodia branch).

Trait-environment association

Across environments, pooled weather data indicated distinct seasonal differences. E1 (*Kharif* 2022) received the highest precipitation (~ 875 mm) under moderate temperatures (26 °C-28 °C) and sunshine (~ 6 hr), whereas E2 (summer 2023) was comparatively drier (~157 mm rainfall) with moderate temperatures (24 °C -30 °C) and longer sunshine duration (5-7 hr). These environmental variations were reflected in the performance of cotton compact traits (Supplementary Fig. S1). In E1, favourable rainfall along with higher temperature and solar radiation promoted better expression of compact traits such as plant height (91.33 cm), sympodial branch length (21.87 cm) and internode length (6.05 cm), which collectively supported higher seed cotton yield (1459.83 kg ha^{-1}). Conversely, in E2, although plant height (89.66 cm), branch length (22.52 cm) and internode length (6.27 cm) were marginally higher, the drastic reduction in precipitation limited yield potential (1415.04 kg ha^{-1}). Overall, the results highlight that favourable weather during E1 (*Kharif* 2022) enhanced compact trait efficiency and yield, whereas moisture stress in E2 (summer 2023) constrained yield realization despite comparable vegetative growth. This indicates that rainfall remains a critical determinant of productivity in compact cotton genotypes under rainfed conditions.

Conclusion

In summary, plant architecture attributes are key factors influencing cotton yield enhancement and suitability for mechanical harvesting. This study explored how plant architecture traits affect seed cotton yield within a specific plant-height range (75 to less than 110 cm). Significant ($p \leq 0.05$) genetic variation was observed in all traits, facilitating selective improvement in genotypes. Genotype, environment and their interactions ($p \leq 0.01$) collectively shaped trait development. Notably, plant height recorded a negative correlation with seed cotton yield in both environments, yielding stable results. Key plant architecture traits influencing yield within the 75 to less than 110 cm height range were identified. Shorter plants exhibited higher yield, whereas increased plant density, absence of monopodia and more sympodial branches showed positive associations with yield. Stepwise regression analysis pinpointed groups of mainstem internode lengths (MIL: 1st, 2nd, 3rd and 4th) and sympodial branch lengths (SBL, lower, middle and upper) as significant factors impacting yield. The study also defined optimal ranges for these traits, providing breeders with actionable targets for selecting genotypes with compact internodes and shorter sympodia that can enhance yield, improve canopy structure and increase efficiency in high-density planting and mechanized harvesting.

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Authors' contributions

BM and BS carried out the field experiment, data collection and statistical analysis. BM and BS contributed to manuscript making and SS, BE, NU, KN, LB, SC, NKJ, KK and SS helped in writing-review and editing of the manuscript. All authors have read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests.

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References

1. Reinhardt D, Kuhlemeier C. Plant architecture. EMBO Rep. 2002;3 (9):846-51. https://doi.org/10.1093/embo-reports/kvf177
2. Madhu B, Sivakumar S, Manickam S, Murugan M, Rajeswari S, Boopathi NM. Improvising cotton (*Gossypium hirsutum* L.) genotypes for compact plant architecture traits suitable for mechanical harvesting. Indian J Genet Plant Breed. 2023;83(03):398-406. https://doi.org/10.31742/ISGPB.83.3.12
3. Yan W, Du M, Zhao W, Li F, Wang X, Eneji AE, et al. Relationships between plant architecture traits and cotton yield within the plant height range of 80–120 cm desired for mechanical harvesting in the Yellow River Valley of China. Agronomy. 2019;9(10):587. https://doi.org/10.3390/agronomy9100587
4. Venugopalan MV, Prakash AH, Kranthi KR, Rachana Deshmukh RD, Yadav MS, Tandulkar NR. Evaluation of cotton genotypes for high density planting systems on rainfed vertisols of central India. In: World Cotton Research Conference-5, Mumbai, India. Excel India Publishers. 2011;341-46.
5. Gunasekaran M, Premalatha N, Kumar M, Mahalingam L, Sakthivel N, Senguttuvan K, et al. Cotton CO17-A short duration, high yielding compact variety suitable for high density planting system. Electron J Plant Breed. 2020;11(4):993-1000. https://doi.org/10.37992/2020.1104.162
6. Williford JR, Brashears AD, Barker GL. Harvesting. In: Anthony WS, Mayfield WD, editors. Cotton Ginners Handb. Collingdale (PA): DIANE Publishing. 1994. p. 11–16.
7. Van der Sluijs MHJ. Harvesting and delivering uncontaminated cotton. Australian cotton production manual-2015. Narrabri, NSW: Cotton Research and Development Corporation. 2015;119-25.
8. Tilak R, Thind SK, Grewal IS. Correlation and path coefficient analysis of yield with yield attributing characters in cotton (*Gossypium hirsutum* L.). Environ Ecol. 2017;35(2C):1228-32.
9. Farias FJ, Carvalho LP, Silva Filho JL, Teodoro PE. Correlations and path analysis among agronomic and technological traits of upland cotton. Genet Mol Res. 2016;15(3):15038239. http://doi.org/10.4238/gmr.15038239
10. Pace PF, Cralle HT, El-Halawany SH, Cothren JT, Senseman SA. Drought-induced changes in shoot and root growth of young cotton plants. J Cotton Sci. 1999;3(4):183-87.
11. Oosterhuis DM. Day or night high temperatures: A major cause of yield variability. Cotton Grower. 2002;46(9):8-9.
12. Su J, Li L, Zhang C, Wang C, Gu L, Wang H, et al. Genome-wide association study identified genetic variations and candidate genes for plant architecture component traits in Chinese upland cotton. Theor Appl Genet. 2018;131:1299-314. https://doi.org/10.1007/s00122-018-3079-5
13. Kaggwa-Asiimwe R, Andrade-Sanchez P, Wang G. Plant architecture influences growth and yield response of upland cotton to population density. Field Crops Res. 2013;145(1):52-59. https://doi.org/10.1016/j.fcr.2013.02.005
14. Wang X, Hou Y, Du M, Xu D, Lu H, Tian X, et al. Effect of planting date and plant density on cotton traits as relating to mechanical harvesting in the Yellow River valley region of China. Field Crops Res. 2016;198:112-21. https://doi.org/10.1016/j.fcr.2016.09.010
15. Konduru S, Yamazaki F, Paggi M. A study of mechanization of cotton harvesting in India and its implications. J Agril Sci Tech B. 2013;3 (11B):789-97.
16. de Mendiburu F, de Mendiburu MF. Package agricolae. R Package. 2019;1(3).
17. Anderson VL, McLean RA. Design of experiments: a realistic approach. CRC Press. 2018. https://doi.org/10.1201/9781315141039
18. Wei T, Simko V, Levy M. Package corrplot. Statistician. 2017;56 (316):24.
19. Lumley T, Miller A. Package LEAPS: Regression subset selection. R package version. 2020;3.
20. Bourgou L, Dever JK, Sheehan M, Kelly CM, Diané SK, Sawadogo M. Diallel crosses of cotton (*Gossypium hirsutum* L.) from Burkina Faso and Texas A & M AgriLife Research-1-Analysis of agronomic traits to improve elite varieties from Burkina Faso. Agronomy. 2022;12 (4):939. https://doi.org/10.3390/agronomy12040939
21. Baxevanos D, Goulas C, Rossi J, Braojos E. Separation of cotton cultivar testing sites based on representativeness and discriminating ability using GGE biplots. Agronomy J. 2008;100 (5):1230-36. https://doi.org/10.2134/agronj2007.0363
22. Ali I, Khan NU, Mohammad F, Iqbal MA, Abbas A, Farhatullah ZB, et al. Genotype by environment and GGE-biplot analyses for seed cotton yield in upland cotton. Pak J Bot. 2017;49(6):2273-83.
23. Xu NY, Fok M, Zhang GW. The application of GGE biplot analysis for evaluating test locations and mega-environment investigation of cotton regional trials. J Integr Agric. 2014;13(9):1921-33. https://doi.org/10.1016/S2095-3119(13)60656-5
24. Bhailume MS, Borole DN, Magar NM. Correlation and path analysis between seed cotton yield and its attributing characters studies in desi cotton. J Cotton Res Dev. 2016;30(1):29-31.
25. Pujer SK, Siwach SS, Sangwan RS, Sangwan O, Jagdish Deshmukh JD. Correlation and path coefficient analysis for yield and fibre quality traits in upland cotton (*Gossypium hirsutum* L). J Cotton Res Dev. 2014;28(2):214-16.
26. Rauf SA, Khan TM, Sadaqat HA, Khan AI. Correlation and path coefficient analysis of yield components in cotton (*Gossypium hirsutum* L.). Int J Agric Biol. 2004;6(4):686-88.
27. Tariq M, Khan AM, Idrees G. Correlation and path coefficient analysis in upland cotton. Sarhad J Agric (Pak). 1992;8(1):341-51.
28. Khan MD, Chaudry NA, Saleem M. Association of various characters in parents and hybrids of *G. hirsutum*. J Pak Cotton. 1979;24(1):253-61.
29. Singh RB, Gupta MP, Mor BR, Jain DK. Variability and correlation studies on yield and quality characters in hirsutum cotton. Indian J Genet. 1968;28(2):216-22.
30. Alkuddsi Y, Patil SS, Manjula SM, Patil BC, Nadaf HL, Nandihali BS. Association analysis of seed cotton yield components and physiological parameters in derived F1 inter specific crosses of cotton. Biosci Methods. 2013;4(1):23-33. https://doi.org/10.5376/bm.2013.04.0005
31. Soomro ZA, Larik AS, Kumbhar MB, Khan NU, Panhwar NA. Correlation and path analysis in hybrid cotton. SABRAO J Breed Genet. 2008;40(1):49-56.
32. Patil HV, Deosarkar DB, Arbad SK. Correlation and path analysis in upland cotton (*Gossypium hirsutum* L.). J Cotton Res. 2017;31(1):19-23.
33. Reddy KB, Reddy VC, Ahamed ML, Naidu TC, Srinivasarao V. Correlation and path coefficient analysis in upland cotton (*Gossypium hirsutum* L.). J Res ANGRAU. 2015;43(1/2):25-35.
34. Wu JR, Hu XM, Zhu QG. A study on the effect of PIX with different seed treatment on the growth of cotton. China Cotton. 1986;2(1):28-29.
35. Fernandez CJ, Cothren JT, McInnes KJ. Partitioning of biomass in

well-watered and water stressed cotton plants treated with mepiquat chloride. Crop Sci. 1991;31(5):1224-28. https://doi.org/10.2135/cropsci1991.0011183X003100050029

36. Kerby TA, Bourland FM, Hake KD. Physiological rationales in plant monitoring and mapping. In: Stewart JMcD, Oosterhuis DM, Heitholt JJ, Mauney JR, editors. Physiology of cotton. Dordrecht: Springer Netherlands. 2010. p. 304-17. https://doi.org/10.1007/978-90-481-3195-2

37. Marois JJ, Wright DL, Wiatrak P. Effect of row width and nitrogen on cotton morphology and canopy microclimate. Crop Sci. 2004;44 (3):870-77. https://doi.org/10.2135/cropsci2004.8700

38. Heitholt JJ. Canopy characteristics associated with deficient and excessive cotton plant population densities. Crop Sci. 1994;34(5):1291 -97. https://doi.org/10.2135/cropsci1994.0011183X003400050028x

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