Global Research journal of Natural Science and Technology (Grjnst)
Volume: 04 - Issue 1 (2026)
p.ISSN: 2790-7643e.ISSN: 2790-7651

Under High Temperature Stress Condition evaluation of Morphological Responses of Cotton (Gossypium hirsutum L.) Genotypes

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DOI: https://doi.org/10.53762/grjnst.04.01.11

Abstract

Cotton cultivation formed an important part of many ancient civilizations and has continued to strengthen the economies and industrial sectors of many countries. Both cotton fiber and cotton seed are economically important due to their extensive use in textile manufacturing and vegetable oil production. With significant alteration of climate and the cotton environmental sensitivity in cultivation, the yield maintenance becomes a great challenge. While the other abiotic stresses to cotton include high temperature, which is one of the most destructive stresses that affect the growth of the plant, flower, fiber quality and yield. This research has been conducted to assess the morphological alteration in various cotton genotypes suffering temperature stress. The set up for the conduct of experiments was performed in the kharif season of 2021. To test the heat stress tolerance among the various cotton (Gossypium hirsutum L.) genotypes, one of locally available experimental fields available was chosen based upon the largest growing ecosystem location of Sindh. Heat stress significantly influenced the node number bearing the first boll. NIA-88 showed the lowest reduction in first boll node number, indicating earlier fruit initiation under stress conditions, while BT-90 and CRIS-121 were delayed. Extreme temperatures above 36 °C adversely influence key morphological and yield-related traits, making heat stress tolerance critical for cotton cultivation. In this study, six genotypes (NIA-88, BT-89, M-32, BT-90, IUB-2013, and CRIS-121) were evaluated under heat stress and non-stress conditions, showing significant variation in plant height, sympodial branches, first boll node, bolls per plant, seed index, seed cotton yield, GOT%, fruiting points, abscission points, fruit retention, and staple length. These findings indicate that each genotype contributes differently to heat tolerance, highlighting the need for multi-trait selection in breeding programs.

Keywords: Cotton, Fiber, Plant, Pakistan, Breed

Introduction

Cotton (*Gossypium hirsutum* L.) is one of Pakistan's most significant export crops and a major cash crop cultivated worldwide. It belongs to the family *Malvaceae* and is a soft, fluffy fiber-producing plant whose fiber is composed of nearly 100% cellulose, making it highly valuable for the textile industry (Saleem et al., 2021). Cotton cultivation formed an important part of many ancient civilizations and has continued to strengthen the economies and industrial sectors of many countries. Both cotton fiber and cotton seed are economically important due to their extensive use in textile manufacturing and vegetable oil production. Cotton is grown in more than 100 countries, including China, India, Pakistan, the United States, Uzbekistan, Australia, and several African nations, and provides employment to nearly 60 million people through production, processing, and allied industries (Shuli et al., 2018). In Pakistan, cotton is one of the most important cash crops and contributes approximately 0.6% to the national GDP and 3.1% to the total value added by agriculture (Malik & Ahsan, 2016). Pakistan ranks among the leading cotton-producing countries of the world; however, cotton area and production have declined in recent years (Kozen & Netravali, 2014). During the 2020–21 season, cultivated area and total production decreased considerably compared to previous years, mainly due to adverse weather conditions, shortage of irrigation water at critical growth stages, and increased insect infestation. Despite its continued economic importance, declining productivity poses a serious threat to the sustainability of cotton production in the country.

Sindh province is a large cotton growing area in Pakistan, with over one million acres of land under cotton cultivation in districts of Hyderabad, Benazirabad, Mirpurkhas, Jamshoro, Naushero Feroz, Badin, Sanghar, Sukkur, Tharparkar, Ghotki, Umerkot and Thatta (Malik & Ahsan, 2016) Both Bt cotton and non-BT cotton varieties are both widely cultivated. Bt cotton usually yields higher per acre and is more adaptable to the current climatic conditions, especially in the lower Sindh (M. A. Ali et al., 2019). Despite the increase in cotton acreage and production in Sindh in the past years, the cotton productivity is still unstable because of the issues of contaminated seed, pest vulnerability, inconsistent supply of irrigation, and climatic stress (Ahmad et al., 2020; Azhar et al., 2020). With significant alteration of climate and the cotton environmental sensitivity in cultivation, the yield maintenance becomes a great challenge. While the other abiotic stresses to cotton include high temperature, which is one of the most destructive stresses that affect the growth of the plant, flower, fiber quality and yield (Abro et al., 2023; Azhar et al., 2020). Increasing global warming and alteration of temperature globally possess a significant concern for the cotton cultivators to recover cotton crops with good yielding capacity. Though the cultivation of cotton is mostly done in hot areas, temperatures that are above the optimum temperature range disorganize the normal physiological and morphological functioning of cotton (Abro et al., 2021). The growth of cotton in May and June months with 35^0C temperature is good but with increase in temperature up to 45^0C which seems common due to global warming harms the optimum growth of cotton. This raised temperature condition harms the overall height of plants, leave area, growth of roots and shoots, flowering, development of bolls and retention of bolls thus eventually compromised the good quality yield (A. Ali & Abdulai, 2010). Despite cotton being the warm season crop but has limited tolerance to long and excessive heat stress which could adversely affect flowering and boll development. The scare data on morphological adjustments of various Gossypium hirsutum L. genotypes to high temperature stressful environment that inhibits successful selection and breeding of heat-resistant cultivars is limited (Bista et al., 2024; Iqbal et al., 2017). Therefore, this research has been conducted to assess the morphological alteration in various cotton genotypes suffering temperature stress. The research could add value by producing genotype specific data on heat stress response that could then be utilized to assist in identifying heat tolerant cotton genotypes with high temperature conditions.

Research Methodology

The set up for the conduct of experiments was performed in the kharif season of 2021. To test the heat stress tolerance among the various cotton (Gossypium hirsutum L.) genotypes, one of locally available experimental fields available was chosen based upon the largest growing ecosystem location of Sindh. The set up for the experiment was a randomized complete block study in a factorial layout, comprising of 4 replications and split-plot design. To trigger the different temperatures situations, two sowing dates were allocated to the main plots, and six cotton genotypes were allocated in the sub plots. To expose the crops to relatively lower temperatures in early growth, sowing was performed in the mid of April. To expose the crop to relatively lower temperatures when the crop is at a relatively lower critical growth stage and reproductive stages, sowing was performed in the mid of May. Thus, expose the crop to higher temperatures in the critical growth and reproductive stages. The experimental materials were six cotton genotypes that included, NIA-88, BT-89, M-32, BT-90, IUB-2013 and CRIS-121. The non-treatment effects were reduced by applying similar uniform agronomic practices during the cultivation period of cotton in the region to eliminate any differences in its growth.

To evaluate genotype reactions to heat stress, morphological, yield, and fiber quality characteristics were measured to determine the data. The height of the plants (cm) was obtained at the ground level to the plant tip with the help of a meter rod. Sympodial branches that bore fruit because of extra-axillary buds were recorded as fruiting and the number of nodes recorded was that at which the first boll emerged. The quantity of bolls per plant was counted by the number of bolls open and unopened. Seed index was determined by weighing 100 randomly chosen seeds in each plot and putting them in grams. The seed cotton production was calculated in terms of a plot (kg plot -1) and translated to kg ha -1. The weight of the seed cotton was calculated using the division by the weight of the lint to give the ginning out turn (GOT %) using the formula: GOT (%) = (weight of lint /weight of seed cotton) × 100. The fruiting points were summed up to the 10th sympodial branch, and the abscission or shedding points were summed up to ascertain the loss of fruits. The percentage of retained fruits in comparison with the total fruiting points was used to determine fruit retention capacity (%) of fruits. The measurements of staple length (mm) were taken by conventional methods of testing fibers.

Results and Discussion

Comparison of six cotton (Gossypium hirsutum L. genotypes) based on two sowing dates indicated that morphological, yield, and fiber related traits varied greatly implying that they responded differently to heat stress conditions (Bista et al., 2024). The analysis of variance shown in Table 1 revealed that the sowing dates, genotypes, and their interactions had significant effects on most of the parameters under investigation, and hence, a high-temperature level in the growing season is a decisive factor in cotton performance.

Table 1: Mean squares from analysis of variances for various traits of cotton

Traits	Genotype (G) (D.F=5)	Treatment (T) (D.F=1)	G × T (D.F =5 = 1)	Error
Plant height (cm)	222.371**	981.021**	411.071**	8.349
Sympodial branches plant^{-1}	70.1705**	29.2188*	0.6491^{NS}	0.9232
GOT%	34.0293**	3.8180**	1.7654**	0.6881
1st boll node number	7.41333**	0.40333^{NS}	0.78333^{NS}	0.35636
Bolls plant^{-1}	120.569**	258.077**	38.091**	3.692
Abscission/shedding points	325.537**	188.021**	61.771**	4.743
Total Fruiting Points	526.127^{NS}	5.535^{NS}	16.694^{NS}	7.516
Fruit retention capacity (%)	347.002**	0.772^{NS}	206.264**	3.075
Seed index (100-seed weight, g)	0.6696**	12.3475**	1.5804**	0.0186
Seed cotton yield (kg plot^{-1})	6.03821**	0.67687^{NS}	0.06288^{NS}	0.05561

Seed Cotton Yield per Hector	428658**	45603^{NS}	4574^{NS}	3798
Staple length (mm)	0.454*	6.02*	0.0021*	0.023

Table 1 shows the detailed means of the performance of genotypes in morphological traits over early sowing and normal sowing conditions. The large genotype sowing date interaction with several traits also demonstrates the importance of adapting characteristic of the genotype at high-temperature conditions as previously described by (EL Sabagh et al., 2020; Sajid et al., 2022).

PLANT HEIGHT (cm)

Table 2 presents the result of plant height expressed in centimeters (cm) under normal condition and under heat stress. In normal conditions, height of plant (cm) was recorded in BT-90 (139.25 cm), accompanied by IUB-2013 (134.5 cm) and M-32 (129.25 cm). While the minimum height recorded Bt-89 (119 cm) and NIA-88 (121 cm). However, IUB-2013 recorded 130 cm followed with CRIS-121 (124 cm) under heat stress condition. The minimum height of plants under normal condition was in BT-90, 38cm while under heat stress minimum height recorded in genotype BT-89 with 116.75cm.

Table 2: **Mean performance for plant height (cm) of cotton genotype**

Genotype	Non-stress SD2	Heat stress SD1	Relative decrease
NIA-88	121.50	120.50	1.00

BT-89	119.00	116.75	2.250
M-32	129.25	122.25	7.00
BT-90	139.25	101.25	38.00
IUB-2013	134.50	130.75	3.75
CRIS-121	126.25	124.00	2.25

Bolls per plant

The results depicted in table 3 for plant-1 bolls under normal and heat stress conditions. Under normal conditions, the maximum bolls plant-1 were recorded in BT-90 (43), accompanied with BT-89 and M-32 (38), and NIA-88 (37.5). While with the minimum bolls plant-1 was recorded in NCRIS-121 (26.75), followed by IUB-2013 (36.75) and NIA-88 (37.5). Under heat stress conditions, the highest bolls plant-1 were noted in NIA-88 (36), with BT-89 (34). However, the minimum bolls plant-1 was grown by CRIS-121 (26.5), with IUB-2013 (33.5). The minimum relative decrease in bolls plant-1 was counted in CRIS-121 (0.25), followed by NIA-88 (1.50). The highest reduction was observed at BT-90 (12.55), following with M-32 (6) and BT-89 (4).

Table 3: Mean performance for Bolls per plant of cotton genotype

Genotype	Non-stress SD2	Heat stress SD1	Relative decrease
NIA-88	37.50	36.00	1

BT-89	38.025	34.00	4
M-32	38.25	36.25	2
BT-90	43.063	30.51	12.55
IUB-2013	36.75	33.25	3.5
CRIS-121	26.75	22.50	4.25

Seed Index

The seed index is considered as an important measurement useful for the assessment of yield. It is a handy indicator to assess the inheritance of quantitative traits impacted by genotype and environmental conditions. Within the normal conditions the seed index peaked was weighed by BT-90 (8.83 g) accompanied with CRIS-121 (8.57 g) and BT-89 (8.17 g), whereas the least seed index was recorded by M-32 (7.59 g), nearly following with IUB-2013 (7.62 g) and NIA-88 (7.9 g), respectively depicted in table 4. Under heat stress conditions, the highest seed index was observed by IUB-2013 (7.89) very nearly accompanied with NIA-88 (7.66 g) and BT-89 (6.98 g). The minimum seed index under heat stress conditions was created by M-32 (6.49 g) followed by CRIS-121 (6.75 g) and BT-90 (6.81 g).

Table 4: Mean performance for seed index of cotton genotype

Genotype	Non-stress SD2	Heat stress SD1	Relative decrease
NIA-88	7.90	7.66	0.24

BT-89	8.172	6.9825	1.189
M-32	7.593	6.4975	1
BT-90	8.83	6.8125	2.0175
IUB-2013	7.6213	7.896	0.1677
CRIS-121	8.5763	6.7587	1.818

Seed Cotton Production

Seed Cotton yield expressed in kg/plot under normal and stress condition has been depicted in table 5. With 7.52 kg NIA-88 displayed the maximum seed cotton yield along with 6.52kg in BT-89. With the least seed cotton yield weight of 5.025 kg in CRIS-121 followed by BT-90 with weight of 5.7 kg. The maximum seed cotton yield was exhibited by NIA-88 with weight of 7.27 kg accompanied with BT-89 with weight 6.4 kg under heat stress condition. On the other hand, BT-90 produced the minimum Seed cotton yield (kg $plot^{-1}$) of 5.12 kg with M-32 (5.2 kg). The minimum relative decline in Seed cotton yield (kg $plot^{-1}$) was observed by CRIS-121 (0.05 kg), followed by IUB-2013 (0.075 kg), whereas the maximum relative deceased was observed in BT-89 (1.125 kg) and BT-90 (0.575 kg).

Table 5: Mean performance for seed cotton yield per plot of cotton genotype

Genotype	**Non-stress SD2**	**Heat stress SD1**	**Relative decrease**
NIA-88	7.525	7.27	0.255

BT-89	6.525	6.400	0.1
M-32	5.425	5.300	0.1
BT-90	5.700	5.125	0.575
IUB-2013	6.100	5.7025	0.4
CRIS-121	5.025	5.000	0.025

Got (%)

GOT% under normal and heat stress conditions has been displayed in Table 6. IUB-2013 had the maximum GOT % and NIA with second best recovery recorded as 40.37% and 38.8%, while BT-90 with 37.1% BT-89 with 37.8%, M-32 and NIA both had 38% of GOT. The maximum Got% under the heat stress condition was displayed6 by IUB-2013 (39.6%), BT-89, NIA-88, and M-32 (37%), followed by BT-90 (36%). The minimum GOT% was recoreded in CRIS-121 (33%), followed by BT-90 (36%). The maximum relative decrease was recorded in CRIS-121 (1.4%), followed by M-32 (1.2%). However, the minimum relative decrease was exhibited in Bt-89 (0.025%), followed by NIA-88 (0.6%).

Table 6: Mean performance for GOT% of cotton genotype

Genotype	Non-stress SD2	Heat stress SD1	Relative decrease
NIA-88	38.00	37.347	0.653
BT-89	37.829	37.099	0.026

M-32	38.875	37.618	1.257
BT-90	37.125	36.065	1.06
IUB-2013	40.375	39.625	0.75
CRIS-121	34.500	33.052	1.44

Total fruiting points

The results for total fruiting points (up to 10th sympodia) at non-stress and heat stress conditions have been recorded in Table 7. Under normal conditions, the maximum total fruiting points (up to 10th sympodia) of 72.7, 61.25, and 58.52 were detected by BT-90, M-32, and BT-89 respectively. However, the minimum total fruiting points (up to 10th sympodia) were exhibited by NIA-88 (52.75) followed by IUB-2013 (57.25). Regarding total fruiting points (up to 10th sympodia) under heat stress conditions, the maximum total fruiting points (up to 10th sympodia) were produced by BT-90 (70), followed by M-32 (56.5) and IUB-2013 (55.75), whereas the minimum total fruiting points (up to 10th sympodia) was observed in CRIS-121 (46.5) followed by BT-89 (55.5). The minimum relative decrease was revealed by NIA-88 (1), followed by IUB-2013 and CRIS-121 (1.5), and BT-90 (2.7), whereas the maximum decrease was exhibited in M-32 (4.75), followed by BT-89 (3.25).

Table 7: Mean performance for Total fruiting points of cotton genotype

Genotype	Non-stress SD2	Heat stress SD1	Relative decrease

NIA-88	52.75	51.75	1
BT-89	58.525	55.50	3
M-32	61.25	56.50	4.75
BT-90	72.763	70.063	2.69
IUB-2013	57.25	40.75	16.5
CRIS-121	48.00	41.50	6.5

Abscission/shedding points

The result for abscission/shedding points for normal and heat stress conditions have been depicted in table 8. BT-90, M-32 and IUB-2013 have the maximum abscission/shedding points of 42, 24 and 22 under normal conditions. The minimum abscission/shedding points were recorded in NIA-88 with 16.75 followed with CRIS-121 with 21.5 and BT-89 with 21. The highest abscission/shedding points was observed by BT-90 with 27 accompanied by M-32 with 23 following with 20 equal to BT-89 and IUB-2013 under the heat condition.

Table 8: Mean performance for Shedding points of cotton genotype

Genotype	Non-stress SD2	Heat stress SD1	Relative decrease
NIA-88	16.75	15.25	1.5
BT-89	21.00	20.50	1.5

M-32	24.00	23.00	1
BT-90	42.25	27.00	15.25
IUB-2013	22.50	19.50	3
CRIS-121	21.50	19.75	1.75

Fruit retention Capacity (%)

The result for the fruit retention capacity in percentage within normal and heat stress condition have been depicted in table 9. BT-IUB-2013 possesses the highest fruit retention capacity with 97.2% with BT-90 having 92% and CRIS-121 with 91% under non-stress condition. The lowest of all under non-stress conditions was recorded in M-32 accompanied with NIA-88 and BT-89 74%, 77% and 81.8% respectively. On the other hand, in thermal stress condition M-32 with 93.3% fruit retention capacity received highest rank. IUB-2013 with 92.1% and the least calculated value in NIA along with 77%. However, IUB-2013 represented the highest reduction under thermal stress conditions.

Table 9: Mean performance for Fruit retention capacity of cotton genotype

Genotype	Non-stress SD2	Heat stress SD1	Relative decrease
NIA-88	77.136	77.072	0.064
BT-89	81.809	79.936	1.873
M-32	74.954	93.31	18.35

BT-90	92.013	91.37	0.643
IUB-2013	97.255	92.179	5.076
CRIS-121	91.941	79.718	12.22

Staple length (mm)

The mean performance regarding this character is presented in table 10 which revealed that the NIA-88 and M-32 measured the longest staple length as compared to other genotypes while variety IUB-2013 showed short staple length in both-stress regimes (March and May regimes). Under Heat stress, a maximum relative decrease of (0.5) was observed in IUB-2013 and CRIS-121 while the minimum relative decrease of (0.2) was observed in NIA-88 and M-32.

Table 10: Mean performance for the staple length of cotton genotype

Genotype	Non-stress SD2	Heat stress SD1	Relative decrease
NIA-88	29.0	28.8	0.2
BT-89	28.5	28.3	0.3
M-32	28.8	28.6	0.2
BT-90	28.0	27.6	0.4
IUB-2013	27.5	27.0	0.5
CRIS-121	28.5	28.0	0.5

Plant height was markedly reduced under normal sowing, which exposed plants to higher temperatures during early vegetative and reproductive stages shown in Table 1. Among the genotypes, IUB-2013 and CRIS-121 maintained comparatively higher plant height under heat stress, whereas BT-90 showed the greatest reduction, indicating higher sensitivity. Reduced plant height under heat stress has been attributed to impaired cell elongation, reduced photosynthetic efficiency, and altered hormonal regulation (Sajid et al., 2022; Zafar et al., 2023). Genotypes that sustain plant height under stress conditions are considered physiologically more resilient, as vegetative vigor contributes to improved assimilate supply during reproductive development. The number of sympodial branches per plant, a critical determinant of fruiting capacity, also declined significantly under high-temperature conditions. IUB-2013 recorded the highest number of sympodial branches under both sowing dates, whereas CRIS-121 exhibited the lowest values and the greatest reduction under heat stress. Similar reductions in sympodial branching under elevated temperatures have been reported by (Azhar et al., 2020), who associated this response with disruption in carbohydrate partitioning and floral initiation. The relatively stable performance of NIA-88 and BT-89 suggests better reproductive adaptability under heat stress.

Heat stress significantly influenced the node number bearing the first boll. NIA-88 showed the lowest reduction in first boll node number, indicating earlier fruit initiation under stress conditions, while BT-90 and CRIS-121 were delayed. Early boll formation under high temperature is advantageous as it allows partial escape from prolonged stress during peak reproductive stages (Azhar et al., 2020; Sajid et al., 2022). This trait is therefore considered an important morphological indicator of heat tolerance. Bolls per plant were significantly reduced under normal sowing across all genotypes. However, NIA-88 maintained the highest boll number under heat stress, followed by BT-89, while BT-90 exhibited the greatest reduction. The decline in boll number under high temperature is mainly due to increased shedding of squares and young bolls caused by pollen sterility and reduced assimilation availability (Abro et al., 2021; Majeed et al., 2021). Genotypes exhibiting lower boll reduction under stress are therefore more desirable for cultivation under warming climates. Yield-related traits showed pronounced sensitivity to heat stress. Seed index declined under normal sowing, with IUB-2013 and NIA-88 showing minimal reduction, whereas BT-90 and CRIS-121 were more adversely affected. High temperature during seed development shortens the filling period and limits assimilate translocation, leading to reduced seed weight (Zafar et al., 2023). Seed cotton yield (kg $plot^{-1}$ and kg ha^{-1}) also declined significantly under heat stress, with NIA-88 producing the highest yield under normal sowing, followed by BT-89. In contrast, BT-90 and CRIS-121 recorded the lowest yields and the highest percentage reduction. These findings are aligned with previous reports that high temperatures beyond 35^0C 40^0C reduce cotton yield by playing a major role in retention and development of bolls (EL Sabagh et al., 2020; Sarwar et al., 2019). Genotype variation in ginning out turn (GOT) was moderate between the heat stress. IUB-2013 had the highest GOT% in both the slowing dates, whereas CRIS-121 had the lowest. The ability to be stable in GOT% during stress indicates effective lint growth and assimilates partitioning to produce fibers (Zafar et al., 2022). Even though GOT% is largely insensitive to yield characteristics, sustained heat stress may adversely affect the development of lint and fiber maturity. High temperatures have a great influence on fruiting behavior. Normal sowing reduced total fruiting points and retention capacity of fruit, especially in M-32 and CRIS-121, suggesting that they were more susceptible to being affected by heat conditions resulting in abscission. Conversely, NIA-88 had greater total fruiting point whereby the decrease was minimal whereas M-32 had a relatively high fruit retention capacity during stress. The process of shedding is amplified by heat stress, which has been widely observed, and associated with hormonal imbalance, decreased pollen viability, and carbohydrate limitation (Abro et al., 2021; Majeed et al., 2021). Heat stress did not change staple length comparatively as it changed yield-related traits. High temperature staple length in NIA-88 and M-32 remained relatively constant, but in IUB-2013 and CRIS-121, it was reduced more. Whereas fiber quality characteristics tend to stay more constant, when confronted with long periods of high temperature there is a limitation to the fiber elongation and cellulose deposition (Ahmad et al., 2020; Azhar et al., 2020). In general, the findings of Table 1 and Table 2 clearly indicate that heat stress has a tremendous effect on morphological development, fruiting behavior, yield, and fiber characteristics in cotton with a significant genotypic variation. Out of the tested genotypes, NIA-88 and BT-89 demonstrated better performance under heat stress because they retained more bolls, yield, and fruit as well as IUB-2013 appeared not to change significantly in terms of sympodial branching, seed index, and GOT%. By comparison, BT-90 and CRIS-121 were more vulnerable to high temperature, exhibiting a larger reduction in most traits. The findings warrant the use of morpho-yield based heat-tolerant cotton genotypes to maintain productivity in conditions of rising temperatures presented by climate change.

Conclusion

Exposure of cotton (Gossypium hirsutum L.) to high temperatures during the growing season significantly affects growth, development, and yield. Extreme temperatures above 36 °C adversely influence key morphological and yield-related traits, making heat stress tolerance critical for cotton cultivation. In this study, six genotypes (NIA-88, BT-89, M-32, BT-90, IUB-

2013, and CRIS-121) were evaluated under heat stress and non-stress conditions, showing significant variation in plant height, sympodial branches, first boll node, bolls per plant, seed index, seed cotton yield, GOT%, fruiting points, abscission points, fruit retention, and staple length. Under thermal stress, IUB-2013 exhibited superior vegetative growth and fiber quality, NIA-88 maintained high bolls per plant, seed cotton yield, and staple length, BT-90 excelled in boll positioning and total fruiting points, and M-32 had the highest fruit retention capacity. These findings indicate that each genotype contributes differently to heat tolerance, highlighting the need for multi-trait selection in breeding programs. NIA-88, BT-90, and M-32 emerged as promising candidates for developing heat-resilient cultivars. Early sowing under field conditions may further aid the identification of high-yielding, heat-tolerant genotypes. Overall, this study underscores the importance of selecting cotton genotypes capable of sustaining growth and yield under rising temperatures, ensuring productivity and economic stability. By enhancing the resilience of cotton crops, this research benefits farmers, supports the textile industry, and contributes to sustainable agriculture. Future work should focus on elucidating the physiological and molecular mechanisms of heat tolerance to accelerate the development of robust cotton varieties.

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