



Check for updates



Research Article

Multivariate Analysis of Elite *Bt* Cotton Genotypes for Seed Cotton Yield and Fiber Quality Traits Under Semi-Arid Conditions

Muhammad Younas¹, Muhammad Zafar², Babar Hussain Babar², Muhammad Jamil³, Muhammad Kashif Munir⁴, Muhammad Mahmud Iqbal⁵, Ali Aziz Awan⁶, Sobia Ijaz⁷, Muhammad Tauseef⁸, Abdul Ghaffar Khan⁹, Musarrat Shaheen¹⁰, Syed Waqar Hussain Shah¹¹, Muhammad Irfan Yousaf¹², Sabir Hussain¹³

¹Oilseed Research Institute, Ayub Agriculture Research Institute, Faisalabad, Pakistan.

²Sugarcane Research Institute, Ayub Agriculture Research Institute, Faisalabad, Pakistan.

³Cotton Research Station, Vehari, Cotton Research Institute, Multan, Pakistan.

⁴Forage Crops Section, Faisalabad, Fodder Research Institute, Sargodha, Pakistan.

⁵Agronomic Research Institute, Ayub Agriculture Research Institute, Faisalabad, Pakistan.

⁶Pulses Research Institute, Ayub Agriculture Research Institute, Faisalabad, Pakistan.

⁷Fiber Crops section, Agronomic Research Institute AARI, Faisalabad, Pakistan.

⁸Cotton Research Institute, Multan, Pakistan.

⁹Soil Fertility (Field), Lahore, Pakistan.

¹⁰Cotton Research Institute, Khanpur, Pakistan.

¹¹Entomological Research Sub-Station, Bahawalpur, Pakistan.

¹²Cotton Research Station, Bahawalpur, Pakistan.

¹³Oilseeds Section, Regional Agricultural Research Institute, Bahawalpur, Pakistan.



*Correspondence

Muhammad Younas

dr_y_javed@yahoo.com

Article History

Received: April 08, 2025

Accepted: April 23, 2025

Published Online: May 01, 2025

Cite this article

Younas, M., Zafar, M., Babar, B. H., Jamil, M., Munir, M. K., Iqbal, M. M., Awan, A. A., Ijaz, S., Tauseef, M., Khan, A. G., Shaheen, M., Shah, S. W. H., Yousaf, M. I., & Hussain, S. (2025). Multivariate analysis of elite *Bt* cotton genotypes for seed cotton yield and fiber quality traits under semi-arid conditions. *Integrative Plant Biotechnology*, 03, 101-111.



Copyright: © 2025 by the authors.

Licensee: Roots Press, Rawalpindi, Pakistan.

This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license:

<https://creativecommons.org/licenses/by/4.0>

ABSTRACT

Cotton production in semi-arid regions like Pakistan is constrained by water scarcity and heat stress, resulting in yields significantly lower than global leaders like China. This study evaluated ten elite *Bt* cotton genotypes (BH-318, BH-348, BH-224, BH-563, BH-405, BH-410, BH-606, BH-248, BH-184, CIM-600) for yield, fiber quality, and associated traits under semi-arid conditions at the Cotton Research Station, Bahawalpur, using a Randomized Complete Block Design with three replications. ANOVA confirmed significant genotypic variation ($p \leq 0.01$) for plant height, nodes, sympodial branches, photosynthetic rate, fiber strength, and yield, with BH-348 and BH-224 achieving the maximum yields (2169.1 kg/ha in Cluster 1). Correlation analysis revealed positive associations between yield and nodes ($r = 0.741^{**}$), plant height ($r = 0.548$), and sympodial branches ($r = 0.416$), while PCA showed PC1 (29.4%) and PC2 (22.6%) explaining 52% of the variation, driven by yield and fiber quality traits, respectively. Cluster analysis grouped genotypes into two clusters, with Cluster-1 (BH-318, BH-348, BH-224, BH-606, BH-410, BH-248) excelling in yield and Cluster-2 (BH-563, BH-405, BH-184, CIM-600) in fiber quality (fiber length: 28.9 mm, fiber strength: 35.4 g/tex). The findings from the present multivariate analyses highlight BH-348 and BH-224 as ideal for yield-focused breeding and BH-563 for quality improvement, offering strategies to enhance cotton productivity and quality in semi-arid environments.

Keywords: Abiotic Stresses, Upland Cotton, Seed Cotton Yield, Fiber quality traits, Multivariate Analysis, Semi-arid conditions

INTRODUCTION

Cotton (*Gossypium hirsutum* L.) accounts for over 35% of global textile fiber production and is a key cash crop in semi-arid regions, particularly in South Asia. In areas like Bahawalpur and Multan, Pakistan, characterized by low rainfall (250–500 mm annually) and high temperatures (often above 40°C), cotton production is constrained by water scarcity and heat stress, which limit boll development and fiber quality.

This result in the reduction of wheat yields (500–1,200 kg ha⁻¹) compared to 1,500–2,000 kg/ha in more favorable climates (Zhangjin et al., 2025). These semi-arid conditions reduce critical fiber quality traits, such as length (27–32 mm), strength (28–32 g/tex), and fineness (3.8–4.5 µg/inch), due to impaired assimilate supply and physiological stress (Majeed et al., 2021). The need for elite cotton strains capable of thriving under such constraints is urgent to ensure sustainable production and meet industrial demands. Exploiting genotypic variation in traits like root depth, stomatal regulation, and photosynthetic efficiency offers a pathway to improving drought resilience and stabilizing yields under stress conditions (Sousa et al., 2025). Pakistan's cotton production and per-acre yield lag behind top producers like China, India, and the United States, where China achieves 1,992 kg/ha through advanced irrigation and mechanized farming, India reaches 1,200–1,500 kg/ha with Bt cotton adoption, and the U.S. benefits from precision agriculture to enhance fiber quality. In contrast, Pakistan faces challenges such as waterlogging from flood irrigation, heavy bollworm infestations, poor soil health, and restricted access to certified, high-yielding seeds resulting in an average yield of just 570.99 kg/ha (USDA, 2024; Javed et al., 2024).

The genetic improvement of cotton, particularly for seed cotton yield, depends on a different agronomic, physiological, and fiber quality traits that collectively determine a genotype's performance under varying conditions, especially in semi-arid environments. Plant height and the number of nodes per plant are foundational architectural traits influencing yield potential. Taller plants with more nodes provide greater opportunities for fruiting positions, directly contributing to higher boll numbers and seed cotton yield, as demonstrated in a study on drought-tolerant cotton genotypes (Li et al., 2022). Sympodial branches, the primary fruiting structures, are critical for yield, with higher numbers strongly correlated with increased boll production and seed cotton yield, a finding supported by recent work in semi-arid regions of India (Lakshmanan et al., 2025). Conversely, monopodial branches, which are vegetative, often contribute less to yield, diverting resources away from reproductive growth, though they can enhance canopy structure under stress conditions (McGarry et al., 2016). Physiological traits like net photosynthetic rate play a pivotal role in cotton's genetic improvement by driving assimilate production for boll and fiber development. Genotypes with higher photosynthetic rates under semi-arid conditions have shown a 15–20% increase in seed cotton yield, as they support greater biomass and boll weight, according to a field study in Australia (Bakhsh et al., 2019). Fiber quality traits—length, fineness, and strength—are equally critical for industrial applications and genetic selection (Ali et al., 2008). Fiber length and strength are positively associated with photosynthetic efficiency, ensuring better cellulose deposition, while fiber fineness often presents a trade-off with yield, as finer fibers may reduce ginning out-turn (GOT) (Raza et al., 2021). Ginning out turn, a key economic trait, ranges from 35–42% in elite strains, with higher values directly enhancing lint yield; a study in Pakistan reported that a 1% increase in GOT can boost seed cotton yield by 50 kg/ha (Shahzad et al., 2022).

Boll weight and seed cotton yield per hectare are ultimate indicators of genetic potential, with boll weight showing a strong positive correlation with yield, as heavier bolls increase lint and seed production under water-limited conditions (Ali and Awan, 2009; Rehman et al., 2020). Recent research identified genotypes with boll weights above 6 g achieving yields of 2,200 kg/ha, even under semi-arid stress, by optimizing assimilate partitioning (Ali et al., 2016). Moreover, integrating these traits into breeding programs has led to the development of high-yielding cotton varieties, with seed cotton yields improving by 10–15% over the past decade through marker-assisted selection targeting sympodial branching and photosynthetic efficiency (Boopathi et al., 2015). These findings underscore the importance of a multi-trait approach in cotton breeding, balancing yield components with fiber quality to meet both agronomic and industrial needs in challenging semi-arid environments. This study aims to evaluate the performance of elite Bt cotton genotypes under semi-arid conditions, focusing on yield, fiber quality, and associated agronomic and physiological traits to identify superior genotypes for breeding programs. For this purpose, multivariate analyses like analysis of variance, correlation analysis, cluster and principal component analysis were performed.

MATERIALS AND METHODS

The study was carried out at the Cotton Research Station in Bahawalpur, Pakistan, a semi-arid area with annual rainfall of 200–300 mm, temperatures of 25–45°C during the cotton season, and clay-loamy soils. A Randomized Complete Block Design (RCBD) with three replications was used to evaluate ten cotton genotypes: eight elite strains (BH-318, BH-348, BH-224, BH-563, BH-405, BH-410, BH-606, BH-248) and two checks varieties i.e., BH-184 and CIM-600. Experimental plots were laid out with a plant-to-plant spacing of 30 cm and a row-to-row spacing of 75 cm to maintain consistent plant density. Sowing was done in the 3rd week of April 2024. Uniform agronomic and pathological management practices were applied across all genotypes, including irrigation every 7 days via application of 200 kg/ha, 100 kg/ha P₂O₅, and 98 kg/ha K₂O using urea, diammonium phosphate, and sulfate of potash, respectively. The soil and irrigation water properties are described in Table 1.

Table 1. Properties of Soil and Irrigation water used during the study

<i>Properties of Irrigation water used in the study</i>		
Sr#	Parameter	Value
1	Total Soluble Salts (TSS)	1167 ppm
2	Sodium Adsorption Ratio (SAR)	6.8
3	Residual Sodium Bicarbonate (RSB)	1.45
<i>Properties of Soil on which the experiment was carried out</i>		
1	Soil Texture	Clay Loamy
2	pH	8.0
3	EC	4.95 dSms
4	Organic Matter	0.73
5	Available P	7.5 ppm
6	Available K	85 ppm
7	Zinc	1.34 ppm

Data Collection

The data collected from ten fully guarded plants on a range of agronomic, physiological, and fiber quality traits to assess genotypic performance of ten cotton genotypes under semi-arid conditions. Agronomic traits, including plant height (PH; cm), number of nodes per plant (Nodes), number of sympodial (Sympodia) and monopodial branches (Monopodia) and boll weight (BW; g), were recorded at physiological maturity by randomly selecting ten plants per plot. Seed cotton yield (kg/ha) was determined by harvesting the entire plot and scaling the weight to a hectare basis after ginning to calculate ginning out-turn (GOT, %). Fiber quality parameters fiber length, strength, and fineness were measured post-harvest using a High-Volume Instrument (HVI-1000, Uster Technologies, Switzerland) on lint samples from each plot. Physiological traits, specifically net photosynthetic rate ($\mu\text{mol m}^{-2} \text{s}^{-1}$) was measured during the boll-filling stage on fully expanded leaves of five randomly selected plants per plot per replication using a portable photosynthesis system (CI-340, LI-COR Biosciences, USA) under ambient conditions.

Statistical Analysis

The collected data were subjected to a comprehensive multivariate analysis to evaluate genotypic performance and trait relationships among ten cotton genotypes. An analysis of Variance (ANOVA) was performed using the RCBD model in R software to test for significant genotypic differences in yield, fiber quality, and agronomic traits. Correlation analysis was conducted to examine the relationships between traits using Pearson's correlation coefficient (Steel *et al.*, 1997; Yousaf *et al.*, 2024). Principal Component Analysis (PCA) was employed to identify the primary sources of variation among genotypes, with variable contributions to PC1 and PC2 assessed to prioritize traits for selection for cotton evaluation and improvement as applied by Afzal *et al.*, 2024. Cluster analysis, using the hierarchical clustering method with Euclidean distance, was applied to group genotypes based on similarity in yield and fiber quality traits, facilitating the identification of distinct performance clusters for breeding purposes (Javed *et al.*, 2024).

RESULTS AND DISCUSSION

Analysis of Variance (ANOVA)

The ANOVA results revealed significant genotypic variation among the ten elite cotton genotypes for most traits evaluated under semi-arid conditions, confirming the presence of significant genetic diversity suitable for breeding programs (Table 2). Genotypes showed highly significant differences for plant height, number of nodes, monopodial branches, sympodial branches, photosynthetic rate, fiber strength, fiber fineness, and yield, indicating that these traits are strongly influenced by genetic factors and can be targeted for selection to improve performance in water-limited environments (Table 3) (Ayub *et al.*, 2020). Fiber length and boll weight showed non-significant genotypic variation, suggesting limited genetic diversity for these traits among the tested genotypes, possibly due to environmental constraints in semi-arid conditions (Singh *et al.*, 2007). Ginning out-turn was significant at $p \leq 0.05$, indicating moderate genetic influence on lint recovery. The means table showed that highest seed cotton yield was given by BH-184 (2747 kg ha^{-1}), followed by BH-405 (2340 kg ha^{-1}) and BH-563 (2210 kg ha^{-1}) (Table 3). Similar findings were also reported by the several researchers who found that genetic diversity present in the cultivated germplasm could be very helpful in improving the existing cultivars and development of new cotton varieties with superior traits (Bhatti *et al.*, 2020a; Mehmood *et al.*, 2024; Hussain *et al.*, 2024a; Hussain *et al.*, 2024b).

Table 2. Mean Square (MS) of key seed cotton yield and quality related traits in cotton genotypes

Traits/Source of Variations	Replications	Genotypes	Error
df	2	9	18
Plant Height	73.2	377.78**	73.68
Number of Nodes per Plant	5.7	17.92**	7.62
Number of Monopodial Branches	1.9	1.466**	0.4555
Number of Sympodia Branches	3.7	58.43**	4.663
Net Photosynthetic Rate	62.5	17.485**	5.13
Fiber Length	0.35	0.682 ^{NS}	0.804
Fiber Strength	21.8261	9.6385*	3.4457
Fiber Fineness	0.0253	0.2096**	0.093852
Ginning Out Turn	0.829	2.4702 ^{NS}	2.7679
Boll Weight	0.18041	0.15173*	0.07007
Seed Cotton Yield	843238	395591**	78590

Note: ** = significant at 1%; * = Significant at 5%, ns = non-significant

Table 3. Mean Performance of ten cotton genotypes based on key seed cotton yield and quality related traits

Gen.	BH-224	BH-248	BH-318	BH-348	BH-405	BH-410	BH-563	BH-606	BH-184	CIM-600	BH-224
PH	96±2.1	123.3±3.3	144.3±9.6	133.3±6	126±4.9	144±7.0	121.3±1.8	131.6±1.8	117.7±5.	120±2.8	96.0±2.1
Nodes	9.0±0.6	19.3±1.2	26.0±1.5	20.3±2.	17.3±0.8	23.0±2.3	18.3±0.3	25.3±1.4	14.7±2.0	15.3±1.7	9.0±0.6
Symp	17.65±2.3	22.66±0.8	21.6±2.9	21.6±4.	18.2±0.5	20.6±.2	18±1.0	17±1.0	18±0.6	19.3±0.8	17.6±2.3
Mono	1.33±0.3	1.0±0.5	1±0.5	1.6±0.8	1.6±0.3	0.7±0.3	1.3±0.3	1.3±0.3	1.7±0.3	1±0.5	1.33±0.3
Pr	26±4	30±3.0	30.3±2.1	24.3±3	26.6±1.7	28±1.2	31.6±1.8	28.7±2.9	26±3.6	27.3±2.6	26±4
FL	28.96±0.6	28.7±0.2	28.7±0.2	28.6±1	28.4±0.3	28.1±0.7	28.7±0.2	28.9±0.5	28.2±0.2	29.4±0.1	28.9±0.6
FS	98.43±1.8	97.7±1.2	104.6±0.3	100.2±3	97.3±2.1	95±0.1	98.6±3.3	98.6±2.6	92.3±0.5	93.2±0.9	98.4±1.8
FF	4.63±0.1	4.7±0.2	4.1±0.03	4.2±0.1	4.5±0.03	4.6±0.1	4.4±0.1	4.6±0.3	4.7±0.1	4.1±0.2	4.6±0.1
GOT	37.6±0.3	40.2±1.4	38.1±1.0	40.9±1	39.5±0.6	40.2±0.1	39.9±0.5	37.3±0.9	40.2±0.4	39.3±0.5	37.6±0.3
BW	2.01±0.1	2.2±0.1	2.2±0.1	1.8±0.1	1.9±0.1	1.9±0.2	2.14±0.2	2.14±0.2	2.01±0.03	2.2±0.2	2.01±0.1
Yield	2173±320	1239±171	1267±133	1702±201	2340±6	1655±40	2210±187	1785±109	2747±254	1137±139	2173±320

Where, Gen: Genotypes, PH: Plant height; Nodes: Number of nodes per plants; Mono: Number of Monopodial Branches; Symp: Number of Sympodial Branches; Pr: Net Photosynthetic rate; FL: Fiber length; FS: Siber strength; FF: Fiber fineness; GOT: Ginning out turn; BW: Boll weight; Yield: Seed cotton yield.

Correlation Coefficient Analysis

The correlation coefficient analysis unveiled the relationships among plant height, number of nodes, monopodial branches, sympodial branches, net photosynthetic rate, fiber length, fiber strength, fiber fineness, ginning out-turn, boll weight, and seed cotton yield for the elite cotton genotypes evaluated under semi-arid conditions, providing insights into trait interdependencies for genetic improvement (Figure 1). Cotton yield showed a strong positive correlation with number of nodes per plant ($r = 0.741^{**}$, $p \leq 0.01$), PH ($r = 0.548$), and number of sympodial branches per plant ($r = 0.416$), indicating that genotypes with more fruiting branches, tall plant stature, and higher fruiting points, such as BH-318 and BH-410, are likely to achieve greater seed cotton yields in water-limited environments. Conversely, cotton yield was negatively correlated with fiber strength ($r = -0.703^*$) and fiber length ($r = -0.316$), suggesting that lengthier and finer fibers may divert resources from reproductive growth, a trade-off also noted by UI-Allah *et al.* (2021).

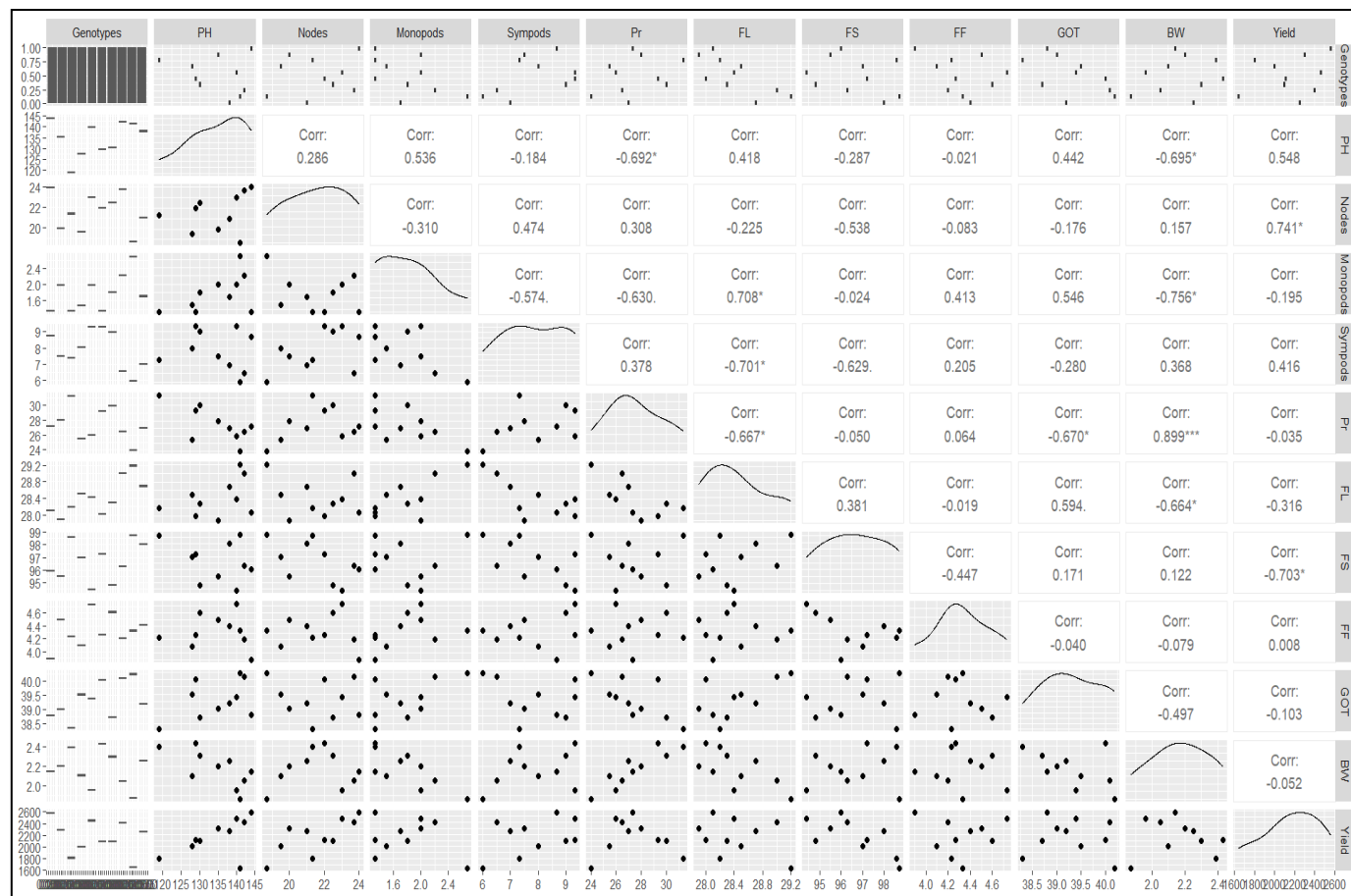


Figure 1. Correlation coefficient between different plant traits in upland cotton genotypes.

Table 4. Cotton genotypes clustering in different clusters.

Sr. No	Genotypes	Cluster No.
1	BH-318, BH-348, BH-224, BH-606, BH-410, BH-248	Cluster-1
2	BH-563, BH-405, BH-184 ©, CIM-600 ©	Cluster-2

Table 5. Class means obtained through cluster analysis of ten cotton genotypes.

Cluster	PH	Nodes	Monopods	Sympods	Pr	FL	FS	FF	GOT	BW	Yield
Cluster 1	131.2	21.4	1.8	8.4	28.7	28.2	33.5	4.3	39.1	2.2	2169.1
Cluster 2	136	17.9	1.3	13.3	26.8	28.9	35.4	4.5	39.2	1.9	2008.2

Where, PH: Plant height; Nodes: Number of nodes per plants; Monopods: Number of Monopodial Branches; Sympods: Number of Sympodial Branches; Pr: Net Photosynthetic rate; FL: Fiber length; FS: Fiber strength; FF: Fiber fineness; GOT: Ginning out turn; BW: Boll weight; Yield: Seed cotton yield.

Net photosynthetic rate exhibited a strong positive correlation with boll weight ($r = 0.899^{**}$) and strength ($r = 0.594^*$), supporting the role of assimilate production in enhancing boll weight, while its negative correlation with PH ($r = -0.692^{**}$), GOT ($r = -0.692^{**}$) and FL ($r = -0.692^{**}$) indicates a potential yield-quality trade-off under semi-arid stress (Koudahe *et al.*, 2024). Additionally, plant height and number of nodes showed a positive correlation ($r = 0.286$), and both plant height and number of nodes were moderately associated with sympodial branches ($r = 0.416$ and 0.474 , respectively), highlighting the structural contribution to boll-bearing capacity, which indirectly supports yield improvement (Mehmood *et al.*, 2024b, Li *et al.*, 2016). These correlations underscore the importance of balancing yield components with fiber quality traits in breeding programs to develop high-performing cotton genotypes for semi-arid regions.

Cluster Analysis

The cluster analysis categorized the ten cotton genotypes into two distinct clusters based on their performance across plant height, number of nodes, monopodial branches, sympodial branches, net photosynthetic rate, fiber length, fiber

strength, fiber fineness, ginning out-turn, boll weight, and seed cotton yield under semi-arid conditions, as shown in the genotype clustering and cluster means tables (Table 4 & 5). The optimal number of clusters graph and dendrogram insights into the hierarchical clustering of the ten cotton genotypes based on their performance under semi-arid conditions (Figure 2). The dendrogram, using Euclidean distance, divided the genotypes into two clusters, with Cluster-1 (BH-318, BH-348, BH-224, BH-606, BH-410, BH-248) forming a tight group indicative of similarity in high-yield traits, and Cluster 2 (BH-563, BH-405, BH-184, CIM-600) showing greater diversity, particularly in fiber quality traits, a grouping validated by the optimal number of clusters graph which identified two clusters as optimal ($k = 2$) (Figure 2) with the highest average silhouette width (0.15), ensuring robust cluster separation (Yousaf et al., 2023). Cluster-1 was characterized by higher yield (2169.1 kg/ha), greater number of nodes per plant (21.4), more net photosynthetic rate ($28.7 \mu\text{mol m}^{-2} \text{s}^{-1}$), and higher boll weight (2.2 g), indicating that these genotypes are well-adapted for maximizing productivity in water-limited environments, a trait desirable for breeding programs targeting yield improvement (Hussain et al., 2023a).

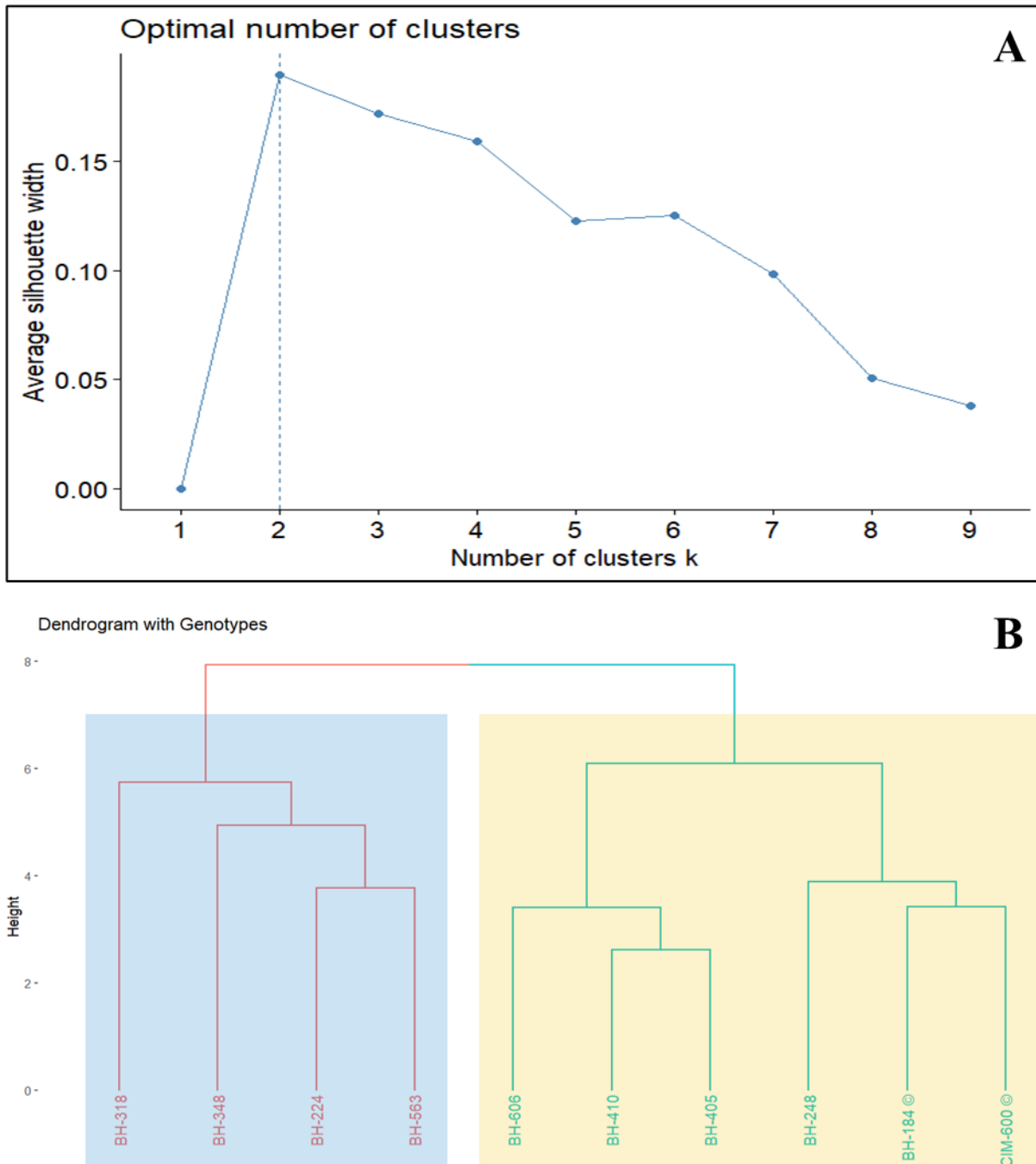


Figure 2. Cluster analysis of *Bt* cotton genotypes for different traits, A) Optimal number of clusters graph, B) Dendrogram.

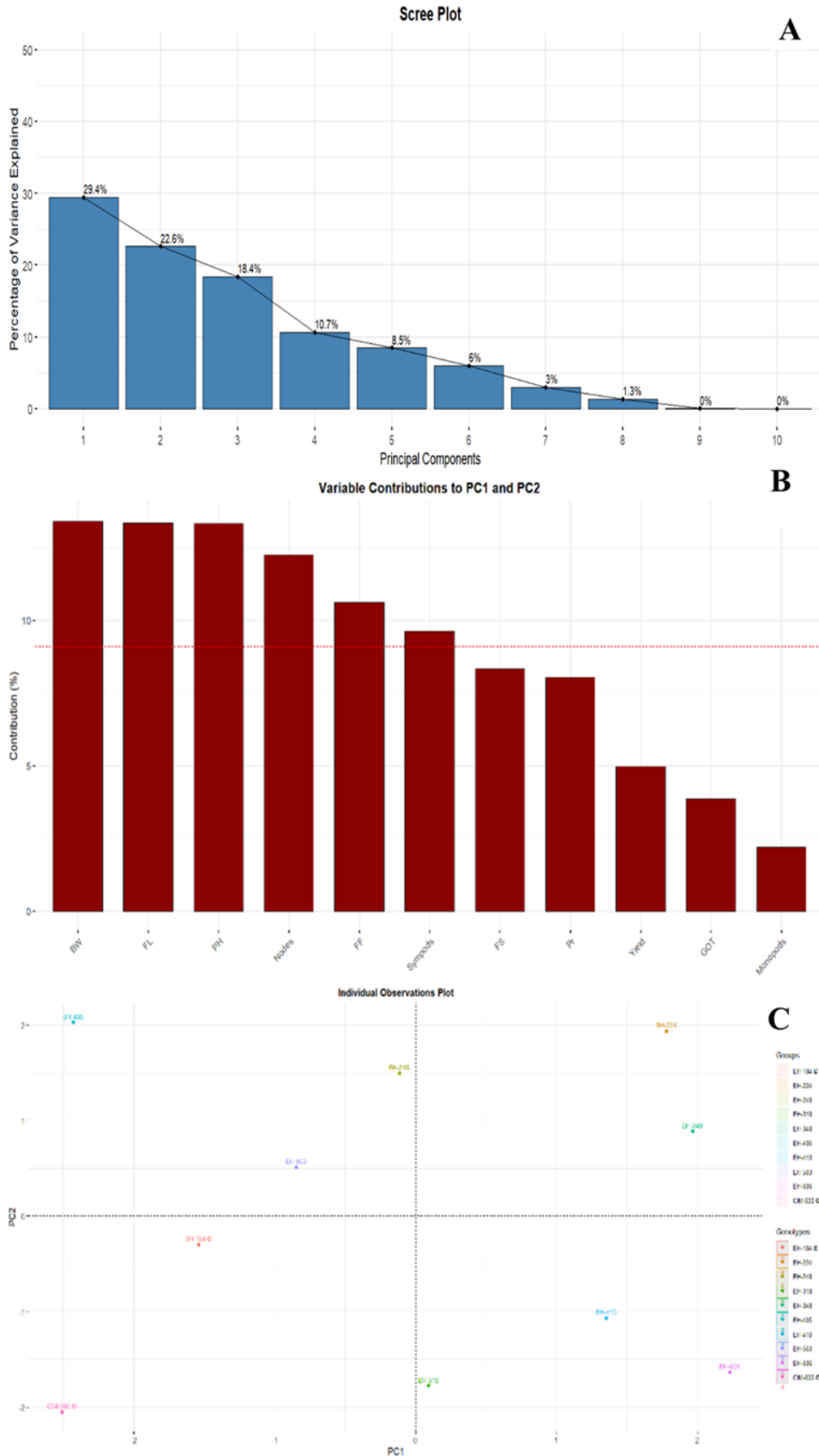


Figure 3: Principal Component Analysis in ten cotton genotypes under study A) Scree Plot of PCA, B) Variable Contribution to PC-1 and PC-2, C) Individual Observation Plot.

In contrast, Cluster 2 exhibited a lower yield (2008.2 kg/ha) but excelled in fiber quality traits, with higher fiber length (28.9 mm), fiber strength (35.4 g/tex), and fiber fineness (4.5 $\mu\text{g}/\text{inch}$), suggesting a focus on quality over quantity, which aligns with the quality-yield trade-off often observed in semi-arid cotton studies (Noreen *et al.*, 2020). Cluster-1 also showed a higher net photosynthetic rate (28.7 $\mu\text{mol m}^{-2} \text{s}^{-1}$) compared to Cluster 2 (26.8 $\mu\text{mol m}^{-2} \text{s}^{-1}$), supporting its yield advantage through better assimilate production, while Cluster-2's higher GOT (39.2%) indicates improved lint recovery despite lower yields (Li *et al.*, 2016). The clustering pattern highlights the genetic diversity among the genotypes, with Cluster-1 genotypes like BH-348 and BH-224 being ideal for yield-focused breeding, and Cluster-2 genotypes like BH-563 and BH-405 offering potential for improving fiber quality in semi-arid conditions, providing a strategic basis for selecting parents for hybridization to combine high yield and quality traits in future cotton varieties (Yousaf *et al.*, 2022). This clustering approach highlights the genetic divergence between yield-focused and quality-focused genotypes, aiding in the selection of diverse parents for breeding programs in semi-arid environments (Yousaf *et al.*, 2022).

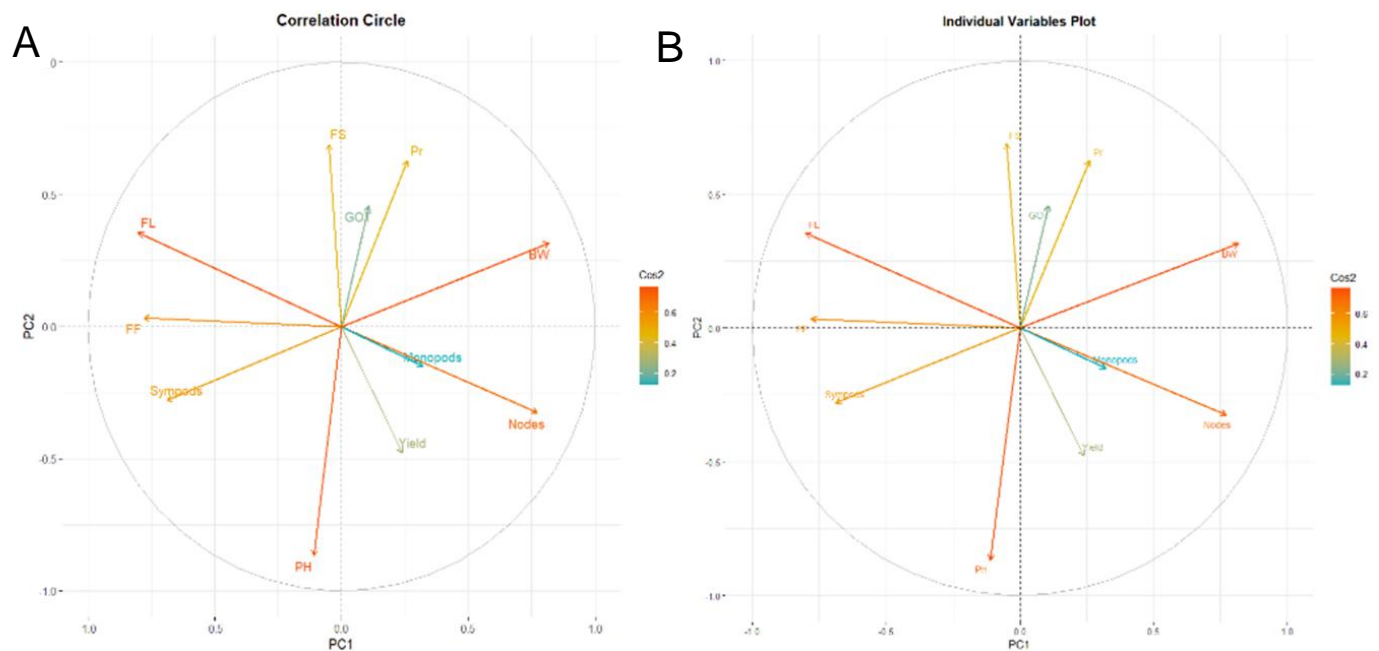


Figure 4: Biplots on the basis of first 2 principal components, A) Correlation Circle of PC-1/PC-2 Biplot, B) Individual Variable Plot of PC-1/PC-2.

Principal Component Analysis (PCA)

The principal component analysis (PCA) provided a comprehensive understanding of the variation among the ten elite cotton genotypes under semi-arid conditions, as illustrated through the scree plot, correlation circle, variable contributions to PC-1 and PC-2, combined PCA biplot, individual variable and individual observations plot (Figures 3 and 4). The scree plot (Figure 3A) indicated that PC-1 and PC-2 together explained a substantial portion of the variance, with PC1 accounting for 29.4% and PC2 for 22.6%, totalling 52% of the variation, suggesting that these components capture the primary sources of trait differentiation among the genotypes, a finding consistent with PCA applications in cotton studies (Hussain *et al.*, 2024a).

The correlation circle (Figure 4A) and individual variables plot (Figure 4B) showed that PC-1 was strongly influenced by yield, sympodial branches, number of nodes, and boll weight, all of which were positively aligned along the positive PC-1 axis, while fiber length and fiber fineness were negatively associated with PC-1, indicating a trade-off between yield and certain quality traits. PC-2 was driven by photosynthetic rate, fiber strength, ginning out-turn, Boll weight and fiber length, which were positively aligned, contrasting with plant height and monopodial branches on the negative PC2 axis, highlighting the role of physiological traits in quality enhancement under semi-arid stress (Hussain *et al.*, 2023b). The variable contributions to PC-1 and PC-2 (Figure 3B) confirmed that BW, FL, PH, and Nodes contributed the most to PC-1 (>10%), while Sympods, FS, and Pr were key contributors to PC-2 (>8%), underscoring their importance in genotypic differentiation (Bhatti *et al.*, 2020a).

The combined PCA biplot and individual observations plot (Figure 3C) positioned genotypes like BH-348, BH-606 and BH-224 along the positive PC-1 axis, close to Nodes, Sympods, and BW, indicating their high-yielding potential,

whereas BH-405, and BH-563, aligned with FL and FF, excelled in fiber quality but had lower yields, and checks like BH-184 and CIM-600 were associated with lower performance across both axes, suggesting limited adaptability to semi-arid conditions (Javed *et al.*, 2024). These PCA results highlight the genetic diversity among the genotypes, enabling the selection of high-yielding strains like BH-348 for productivity and quality-focused strains like BH-563 for breeding programs in semi-arid environments.

CONCLUSION

This study identified significant genotypic variation among ten elite cotton strains under semi-arid conditions, providing a foundation for breeding programs to improve yield and fiber quality in water-limited regions like Bahawalpur, Pakistan. Genotypes in Cluster 1, such as BH-348 and BH-224, demonstrated superior yield potential (2169.1 kg/ha), driven by higher nodes, sympodial branches, and boll weight, making them suitable for enhancing productivity in semi-arid environments. In contrast, Cluster 2 genotypes like BH-563 excelled in fiber quality traits (fiber length: 28.9 mm, fiber strength: 35.4 g/tex), despite lower yields (2008.2 kg/ha), offering potential for meeting industrial quality demands. The strong correlations between yield and traits like nodes ($r = 0.741^{**}$) and sympodial branches ($r = 0.416$), alongside PCA results showing yield and quality as primary sources of variation emphasize the need for a balanced selection approach. By leveraging the genetic diversity identified through cluster and PCA analyses, breeders can use genotypes like BH-348 for yield improvement and BH-563 for quality enhancement, facilitating the development of resilient, high-performing cotton varieties through hybridization to support sustainable production in semi-arid regions.

AUTHOR CONTRIBUTIONS

Younas, Yousaf, Hussain Tauseef, Shah; Writing – original draft; Zafar, Babar, Jamil, Munir, Iqbal, Awan, Ijaz, Khan, Shaheen; Writing – review & editing, Yousaf, Younas, Hussain; Formal analysis, Conceptualization, Validation, Supervision, Resources, Funding acquisition; Zafar, Babar, Jamil, Tauseef; Statistical Analysis. Iqbal, Awan, Shaheen, Khan; Graphic improvement.

CONFLICT OF INTEREST,

The authors declare that they have no conflict of interest.

ACKNOWLEDGEMENTS

The authors express their deepest gratitude to Mr. Rahil Shehzad, Scientific Officer, and Dr. Waseem Akbar, Principal Scientist, Agriculture Biotechnology Research Institute, AARI Faisalabad for their help in reviewing and improving the manuscript.

REFERENCES

- Afzal, S., Shahid, M. R., Khan, M. M., Hameed, A., Rahman, A. U., Tauseef, M., Kausar, S., Bilal, M., Khaliq, A., Kanwal, N., Ali, F., Khalid, M., Aslam, M., Rehman, H. U., Nadeem, A., Shah, S. W. H., Hussain, S., & Yousaf, M. I. (2024). Genotypic performance evaluation of elite cotton stains based on plant traits related to cotton yield, fiber quality, and insect/disease tolerance under heat stress. *Biological and Clinical Sciences Research Journal*, 5, 904.
- Ali, M.A., Khan, I. A., Awan, S. I., Ali, S. & Niaz, S. (2008). Genetics of fibre quality traits in cotton (*Gossypium hirsutum* L.). *Australian Journal of Crop Science*, 2(1), 10-17
- Ali, M.A., & Awan, S. I. (2009). Inheritance pattern of seed and lint traits in *Gossypium hirsutum* L. *International Journal Agriculture & Biology*, 11(1), 44-48.
- Ali, I., Shakeel, A., Ali, A., & Sadia, B. (2016). Genetic basis of variation for within-boll yield components in cotton. *Turkish Journal of Agriculture and Forestry*, 40(1), 18-24.
- Ayub, Q., Khan, S. M., Mehmood, A., Haq, N. U., Ali, S., Ahmad, T., Ayub, M.U., Hassan, M., Hayat, U. & Shoukat, M. F. (2020). Enhancement of physiological and biochemical attributes of okra by application of salicylic acid under drought stress. *J. Hortic. Sci. Technol*, 3(4), 113-119.
- Singh, R. P., Prasad, P. V., Sunita, K., Giri, S. N., & Reddy, K. R. (2007). Influence of high temperature and breeding for heat tolerance in cotton: a review. *Advances in agronomy*, 93, 313-385.
- Bakhsh, A., Salman, M. R. S., & Ullah, R. (2019). Evaluation of cotton genotypes for seed cotton yield and fiber quality traits under water stress and non-stress conditions. *Sarhad Journal of Agriculture*, 35: 161–170.
- Bhatti, M. H., Yousaf, M. I., Ghani, A., Arshad, M., Shehzad, A., Mumtaz, A., Khalid, M. U. Khalid, M. Z., Mushtaq, M.Z. & Shah, S. A. S. (2020a). Assessment of genetic variability and traits association in upland cotton (*Gossypium hirsutum* L.). *International Journal of Botany Studies*, 5(2), 148-151.

- Boopathi, N. M., Sathish, S., Kavitha, P., Dachinamoorthy, P., & Ravikesavan, R. (2015). Molecular breeding for genetic improvement of cotton (*Gossypium* spp.). *Advances in plant breeding strategies: breeding, biotechnology and molecular tools*, 613-645.
- Hussain, A., Jamil, S., Bilal, M., Nadeem, A., Kausar, S., Umer, F., Akram, F., Haq, A. U. L., Quayum, M. A., Butt, B., Qamar, M. J., Iqbal, R. A., Ahmad, R. T., Shakir, M. S., Hussain, S., & Yousaf, M. I. (2024a). Impact of water stress on cotton physiology, ROS accumulation and antioxidant activity in upland cotton genotypes. *Biological and Clinical Sciences Research Journal*, 5, 919.
- Hussain, S., Khan, M. M., Talib, I., Khalid, M., Zubair, M., Murtaza, G., Akhtar, I., Qamar, M. J., Farooq, M. R., Ashfaq, M., Bukhari, M. S. J., Shah, S. W. H., Ali, B., Nayab, S. F., Akram, M. I., Nazar, S., Kausar, S., Asif, M., Jamil, S., Rehman, S., Saleem, M., Luqman, M., & Yousaf, M. I. (2024b). Genetic characterization and performance evaluation of elite cotton strains for morphological and physio-chemical traits under heat stress conditions. *Biological and Clinical Sciences Research Journal*, 5, 725.
- Hussain, S., Aslam, M. Z., Yousaf, M. I., Iqbal, J., Bukhari, M. S. I., Ali, F., Ashfaq, M., Qamar, M. I., Farooq, M. R., Hafeez, Z., Akhtar, I., & Shah, S. W. H. (2023a). Quantitative effects of heat stress on fiber-related and agronomically important parameters in cotton (*Gossypium hirsutum* L.). *Biological and Clinical Sciences Research Journal*, 4, 210.
- Hussain, S., Aslam, M. Z., Qamar, M. J., Farooq, M. R., Murtaza, G., Sajjad, M., Fatima, N. H., Zubair, M., Shah, S. W. H., Ibrar, I., Hafeez, Z., Ali, F., Ashfaq, M., Ahmad, I., & Yousaf, M. I. (2023b). Genetic characterization of cotton genotypes based on morpho-physiological, biochemical, and disease-associated traits through multivariate approaches. *Biological and Clinical Sciences Research Journal*, 3, 373.
- Javed, I., Ashraf, S., Parveen, N., Jamil, M., Ghaffar, W., Sardar, A., Qamar, M. J., Farooq, M. R., Saleem, S., Habib, F., Akram, M. I., Javeed, Z., Khalid, M., Latif, M. I., Rauf, A., Hussain, F., Ali, B., Hassan, W., Manzoor, N., Yousaf, M. I., & Hussain, S. (2024). Role of photosynthetic stability and physio-chemical attributes in the selection of improved cotton genotypes in actual field conditions. *Biological and Clinical Sciences Research Journal*, 5, 199.
- Koudahe, K., Aguilar, J., Djaman, K., & Sheshukov, A. Y. (2024). Evapotranspiration, fiber yield and quality, and water productivity of cotton (*Gossypium hirsutum* L.) under different irrigation technologies in a semiarid climate. *Irrigation Science*, 42(3), 575-594.
- Lakshmanan, S., Somasundaram, S., Shri Rangasami, S., Anantharaju, P., Vijayalakshmi, D., Ragavan, T., & Dhamodharan, P. (2025). Managing cotton canopy architecture for machine picking cotton via high plant density and plant growth retardants. *Journal of Cotton Research*, 8(1), 2.
- Li, C., Zhang, J., Hu, G., Fu, Y., & Wang, Q. (2016). Association mapping and favorable allele mining for node of first fruiting/sympodial branch and its height in Upland cotton (*Gossypium hirsutum* L.). *Euphytica*, 210, 57-68.
- Li, H., Liu, Z., Chen, Y., Zhang, X., & Chen, D. (2022). A positive correlation between seed cotton yield and high-efficiency leaf area index in directly seeded short-season cotton after wheat. *Field Crops Research*, 285, 108594.
- Majeed, S., Rana, I. A., Mubarik, M. S., Atif, R. M., Yang, S. H., Chung, G., Jia, Y., Du, X., Hinze, L. & Azhar, M. T. (2021). Heat stress in cotton: a review on predicted and unpredicted growth-yield anomalies and mitigating breeding strategies. *Agronomy*, 11(9), 1825.
- McGarry, R. C., Prewitt, S. F., Culpepper, S., Eshed, Y., Lifschitz, E., & Ayre, B. G. (2016). Monopodial and sympodial branching architecture in cotton is differentially regulated by the *Gossypium hirsutum* SINGLE FLOWER TRUSS and SELF-PRUNING orthologs. *New Phytologist*, 212(1): 244-258.
- Mehmood, A., Naveed, K., Ayub, Q., Alamri, S., Siddiqui, M. H., Wu, C., Wang, D., Saud, S., Banout, J., Danish, S. & Fahad, S. (2021). Exploring the potential of moringa leaf extract as bio stimulant for improving yield and quality of black cumin oil. *Scientific reports*, 11(1), 24217.
- Mehmood, A., Naveed, K., Khan, S. U., Farid, A., Khan, S. M., Hussain, Q., Akmal, M., Arif, M., Amanullah, Ahmed, M. & Fahad, S. (2024). Mitigating Adverse Effects of Salinity Through Foliar Application of Biostimulants. In *Environment, Climate, Plant and Vegetation Growth* (pp. 115-132). Cham: Springer Nature Switzerland.
- Mehmood, A., Naveed, K., Liu, K., Harrison, M. T., Saud, S., Hassan, S., Nawaz, T., Dhara, B., Dai, D.Q., Ali, I. & Fahad, S. (2024). Exogenous application of ascorbic acid improves physiological and productive traits of *Nigella sativa*. *Heliyon*, 10(7).
- Noreen, S., Ahmad, S., Fatima, Z., Zakir, I., Iqbal, P., Nahar, K., & Hasanuzzaman, M. (2020). Abiotic stresses mediated changes in morpho-physiology of cotton plant. *Cotton Production and Uses: Agronomy, Crop Protection, and Postharvest Technologies*, 341-366.
- Qamar, M.J., Qazi, M.A., Tariq, M., Jawad, H., Shabir, M.A., Arif, M., Farooq, M.R., Iqbal, M.N., Hafeez, Z., Bashir, M.A., Jamil, S., Bashir, F., Rauf, A., Illahi, W., Nazar, M.Z.K, Rafique, H.M., Ghafoor, M.A., Latif, M.I., Yousaf, M.I., & Raza, N. (2024). Assessment Of Wheat Genotypes for Their Low Nitrogen Use Efficiency Under Semi-Arid Conditions of Punjab, Pakistan. *Biological and Clinical Sciences Research Journal*, 2024(1), 1195. <https://doi.org/10.54112/bcsrj.v2024i1.1195>
- Raza, I., Hu, D. W., Ahmad, A., Li, H., He, S., & Nazir, M. F. Correlation analysis of stem hardness traits with fiber and yield-related traits in core collections of *Gossypium hirsutum*. *Journal of Cotton Research* 4: 8.

- Rehman, A., Mustafa, N., Du, X., & Azhar, M. T. (2020). Heritability and correlation analysis of morphological and yield traits in genetically modified cotton. *Journal of cotton research*, 3, 1-9.
- Shahzad, K., Mubeen, I., Zhang, M., Zhang, X., Wu, J., & Xing, C. (2022). Progress and perspective on cotton breeding in Pakistan. *Journal of Cotton Research*, 5(1): 29.
- Sousa, R.O.D., Jesus, J.F.D., da Silva, M.N., Paula-Marinho, S.D.O., Alcântara Neto, F.D., Carvalho, H.H.D., Costa, J.H., Silva, R.F.D., Dauala, G.A., Silveira, M.V.D.S. & Miranda, R.D.S. (2025). Photosynthetic Efficiency and Water Status as Determinants for the Performance of Semiarid-Adapted Cotton Cultivars Under Drought in Greenhouse. *Agronomy*, 15(2), 500.
- Steel, R. G. D., Torrie, J. H. and Dickey, D. A. (1997). *Principles and Procedures of Statistics: A Biometrical Approach*, 3rd Ed. McGraw Hill Book Co., New York.
- UI-Allah, S., Rehman, A., Hussain, M., & Farooq, M. (2021). Fiber yield and quality in cotton under drought: Effects and management. *Agricultural Water Management*, 255, 106994.
- USDA (United States Department of Agriculture). (2024). *Cotton: World Markets and Trade*. Washington, DC: USDA Foreign Agricultural Service.
- Yousaf, M. I., Ghani, A., Zubair, M., Talib, I., Kausar, S., Akhtar, I., Murtaza, G., Rehman, S., Bukhari, M. S. J., Nazar, S., Qamar, M. J., Akram, F., Ashfaq, M., Shah, S. W. H., Ali, B., Sharif, S., Luqman, M., Asif, M., Jamil, S., Sattar, A., Hafeez, Z., Khalid, M., & Hussain, S. (2024). Role of antioxidants accumulation and photosynthetic stability for sustainable cotton production and fibre quality under water stress conditions. *Biological and Clinical Sciences Research Journal*, 5, 726.
- Yousaf, M. I., Hussain, Q., Alwahibi, M. S., Aslam, M. Z., Khalid, M. Z., Hussain, S., Zafar, A., Shah, S. A. S., Abbasi, A. M., Mehboob, A., Riaz, M. W., & Elshikh, M. S. (2022). Impact of heat stress on agro-morphological, physiochemical and fiber related parameters in upland cotton (*Gossypium hirsutum* L.) genotypes. *Journal of King Saud University – Science*, 35, 102379.
- Yousaf, M. I., Hussain, S., Aslam, M. Z., Shah, S. W. H., Zubair, M., Ibrar, I., Akhtar, I., Hafeez, Z., Qamar, M. J., Farooq, M. R., Ashfaq, M., Ali, F., Fatima, N. H., Murtaza, G., Ullah, S., & Ahmad, I. (2023). Evaluation of upland cotton genotypes for morphometric, photosynthesis-related traits and parameters related to enzymatic and non-enzymatic antioxidant accumulation. *Biological and Clinical Sciences Research Journal*, 4, 375.
- Zhangjin, Soothar, R. K., Shar, S. U., Alharthi, B., Shaikh, I. A., Laghari, M Das Suthar, J., Samoon, A., Jamali, N.A., Fiaz, S. & Soomro, A.S. (2025). Responses of cotton yield and water productivity to irrigation management: assessment of economic costs, interactive effects of deficit irrigation water and soil types. *Discover Life*, 55(1), 1.