



Role of Photosynthetic Rate and Transpiration Efficiency in Fibre and Lint Yield Improvement of Upland Cotton Genotypes in Clay-Loamy Soils

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Abstract

Upland cotton (*Gossypium hirsutum* L.) is a critical economic and most valued crop in Pakistan, yet its lint yield remains below global benchmarks, particularly in challenging environmental stresses. This study evaluated the role of key physiological and agronomic traits in improving lint yield and fiber quality among ten genotypes (BH-249, BH-299, BH-226, BH-254, BH-306, BH-224, BH-188, BH-345, BH-184, and CIM-600) at the Cotton Research Station, Bahawalpur, using a Randomized Complete Block Design with three replications. Significant genotypic variation ($p \leq 0.01$) was observed for physiological traits, with photosynthetic rate ($24.64\text{--}30.33 \mu\text{mol m}^{-2} \text{s}^{-1}$) and stomatal conductance ($257.6\text{--}340.3 \text{mmol m}^{-2} \text{s}^{-1}$) strongly correlated with lint yield ($r = 0.50^*$ and 0.95^{**} , respectively). BH-226 achieved the highest yield at 4.56 ± 0.24 t/ha, driven by superior sympodial branching (21.66 ± 2.02) and opened bolls (55.3 ± 6.06), while BH-249 and BH-299 excelled in physiological efficiency. Principal Component Analysis revealed that PC1 and PC2 explained 59% of the variance, with yield aligning closely with sympodial branches and photosynthetic traits, indicating a strong correlation between them. Fiber quality traits like length ($28.53\text{--}29.16$ mm) and strength ($29.5\text{--}32.5$ g/tex) showed moderate associations with physiological parameters, but a trade-off was noted between fiber fineness and ginning out-turn ($r = -0.66^*$). These findings highlight the potential of selecting genotypes with enhanced photosynthetic and transpirational efficiencies to boost lint yield

in Pakistan's clay-loamy soils, offering a pathway to bridge the yield gap with global leaders like China (1,992 kg/ha) while maintaining fiber quality.

Keywords: Stomatal conductance, ginning out-turn, genotypic variation, semi-arid conditions

1. Introduction

Cotton (*Gossypium hirsutum L.*), commonly known as Upland cotton, is a cornerstone of global agriculture, celebrated as the leading natural fiber crop and a vital economic asset. Globally, it occupies approximately 33–35 million hectares, accounting for about 2.5% of arable land, and yields over 70 million tons of seed cotton annually, with an average lint yield of around 800 kg/ha across diverse agroecological conditions (FAO, 2023). Leading producers like China, India, the United States, and Pakistan contribute over 70% of global production, with China achieving yields up to 1,992 kg/ha through advanced irrigation and management practices (USDA, 2024). In Pakistan, cotton is a mainstay of the agrarian economy, cultivated on 2.143 million hectares, primarily in Punjab and Sindh, producing approximately 9.86 million bales annually (Pakistan Bureau of Statistics, 2023). However, the national average yield of 570.99 kg/ha falls short of its potential and global benchmarks, constrained by biotic stresses, climate variability, and suboptimal soil management, especially in clay-loamy soils prevalent in key cotton-growing regions (Siyal et al., 2022). These soils challenge plant height and branching patterns, with studies showing that taller plants (80–120 cm) with more sympodial branches (15–20 per plant)—fruiting structures—correlate with higher boll numbers and yield per hectare (Bednarz et al., 2005).

Photosynthesis and transpiration are critical physiological processes underpinning cotton production, directly influencing lint yield and fiber quality through their effects on plant architecture and physiology. Photosynthesis fuels biomass accumulation and boll development, with higher rates linked to increased carbohydrate availability, enhancing boll weight (averaging 4–6 g) and ginning out-turn (typically 35–40%) (Pettigrew, 2004). Research demonstrates that genotypes with elevated photosynthetic rates exhibit more sympodial branches compared to monopodial branches (1–3 per plant), boosting yield potential (Constable & Rawson, 1980). Transpiration, regulated by stomatal conductance (typically 0.2–0.5 mol m⁻² s⁻¹ in cotton), maintains plant temperature and nutrient uptake, crucial in clay-loamy soils with high water retention but poor aeration (Radin, 1992). Stomatal conductance influences water-use efficiency, supporting plant height and sustaining growth under moisture stress (Taiz & Zeiger, 2010). These processes collectively determine

yield per hectare, with top-performing genotypes achieving 1,500–2,000 kg/ha in favorable conditions, far exceeding Pakistan’s average (Saranga et al., 2001).

The interplay between photosynthetic rate and transpirational efficiency profoundly impacts fiber quality traits—length, fineness, and strength—alongside yield components like boll weight and ginning out-turn. Fiber length (25–32 mm in Upland cotton) and strength (28–32 g/tex) depend on assimilate supply from photosynthesis during boll filling, while fineness (3.8–4.5 µg/inch) reflects efficient water and nutrient transport via transpiration (Bradow & Davidonis, 2000). Studies show that genotypes with higher stomatal conductance produce stronger, finer fibers due to enhanced cellulose synthesis (Khan et al., 2018). In Pakistan, where Upland cotton dominates 95% of cultivated varieties, optimizing these traits in clay-loamy soils could improve ginning out-turn (currently 33–38%) and bridge the yield gap (Mollae et al., 2019). Literature highlights that boll weight and sympodial branching increase lint yield, while monopodial branches contribute less to reproductive output (Oosterhuis, 1990). This study examines how photosynthetic and transpiration efficiencies in Upland cotton genotypes influence these agronomic and quality parameters, offering strategies for sustainable improvement in challenging soil environments.

Pakistan’s lower cotton production and per-acre yield, compared to top producers like China, India, and the United States, stem from multiple constraints that hinder physiological and agronomic performance. Unlike China’s mechanized farming and drip irrigation systems, which optimize water use and boost stomatal conductance, Pakistan relies heavily on flood irrigation, leading to waterlogging in clay-loamy soils and reduced boll weight and fiber quality (Sajid et al., 2024). Pest pressures, notably from bollworms, reduce sympodial branching and yield per hectare, while inadequate access to high-yielding varieties limits plant height and ginning out-turn compared to India’s Bt cotton hybrids, which achieve yields of 1,200–1,500 kg/ha (Marral et al., 2023). Soil fertility decline, erratic rainfall, and limited adoption of precision agriculture further exacerbate the gap, with the United States leveraging advanced nutrient management to enhance fiber length and strength (USDA, 2024). Addressing these constraints through genotype selection and improved management could align Pakistan’s cotton productivity with global leaders.

Materials and Methods

Study Site

The experiment was conducted at the Cotton Research Station, Bahawalpur, located in Punjab, Pakistan (29.39°N, 71.69°E, altitude 116 m). The site is characterized by a semi-arid climate with clay-loamy soils, typical of major cotton-growing regions in the country. The soil texture comprises approximately 35% clay, 40% silt, and 25% sand, with a pH range of 7.8–8.1 and organic matter content of 0.75 – 0.85%, as determined by prior soil analysis.

Experimental Design and Treatments

The study was laid out in a Randomized Complete Block Design (RCBD) with three replications. Ten Upland cotton (*Gossypium hirsutum* L.) genotypes were evaluated, including eight test genotypes (BH-249, BH-299, BH-226, BH-254, BH-306, BH-224, BH-188, BH-345) and two check varieties (BH-184 and CIM-600). Each genotype was sown in plots arranged in a systematic pattern to account for spatial variability within the field. The experimental unit consisted of rows with a plant-to-plant distance of 30 cm and a row-to-row distance of 75 cm, ensuring uniform plant density across all treatments.

All genotypes received identical agronomic and pathological treatments to minimize confounding variables and isolate the effects of genotypic differences in photosynthetic rate, transpirational efficiency and other key agronomic traits. Sowing was performed manually during the 1st week of May, 2024 followed by standard irrigation practices using canal water supplemented by tube-well sources. Fertilizer application included 220 kg N ha⁻¹, 100 kg P₂O₅ ha⁻¹, and 95 kg K₂O ha⁻¹, applied as urea, diammonium phosphate, and sulfate of potash, respectively, based on soil test recommendations. Pest and disease management followed integrated pest management (IPM) protocols, with regular scouting and need-based applications of approved insecticides and fungicides. Weeds were controlled manually and through pre-emergence herbicide application to maintain a weed-free environment throughout the growing season.

Data Collection

Data were recorded on key physiological, agronomic, and fiber quality parameters, including plant height (PH), nodes per plant (Nodes), number of sympodial (Sympodia) and monopodial branches (Monopodia), unopened bolls per plant (UB), opened bolls per plant (OB), photosynthetic rate (Pr), stomatal conductance (Ci), transpiration rate (Tr), fiber length (FL), fiber fineness (FF), fiber strength (FS), ginning out-turn (GOT), boll weight (BW) and lint yield per hectare (Yield). Photosynthetic rate, stomatal conductance and transpiration rate were measured using a portable photosynthesis system (CI-340, LI-COR Biosciences, USA)

on fully expanded leaves during the boll-filling stage under ambient conditions. Agronomic traits were assessed at physiological maturity, while fiber quality parameters were analyzed post-harvest using a High-Volume Instrument (HVI-1000, Uster Technologies, Switzerland). Yield per hectare was calculated based on lint harvested from each plot and extrapolated to a hectare basis.

Statistical Analysis

Data were subjected to analysis of variance (ANOVA) using the RCBD model to determine significant differences among genotypes (Steel et al., 1997). Means were compared using the Least Significant Difference (LSD) test at a 5% probability level ($p \leq 0.05$). Statistical analyses were performed with the software package Statistix 8.1 (Analytical Software, USA) and R (R Core Team, New Zealand). Correlation analysis was conducted to explore relationships between key physiological and agronomic traits including lint yield. Furthermore, principal component and biplot analysis were conducted to categorize cotton genotypes based on their performance as used by Yousaf *et al.* (2023) and Hussain *et al.* (2024).

Results and Discussion

Analysis of Variance (ANOVA) and Mean Performance

The results obtained from the analysis of variance (ANOVA) revealed the presence of significant variations among cotton genotypes for all the studied traits including plant height, nodes per plant, number of sympodial and monopodial branches (Monopodia), unopened bolls per plant, opened bolls per plant, photosynthetic rate, stomatal conductance, transpiration rate, fiber length, fiber fineness, fiber strength, ginning out-turn, boll weight and lint yield per hectare (Table 1). Genetic diversity within data and germplasm is essential for advancing the development of new plant varieties, such as cotton, by supplying the variability required for breeding programs to produce enhanced cultivars. Numerous studies have demonstrated that differences in key traits among cotton strains establish a robust foundation of variability, enabling breeding initiatives aimed at enhancing existing genotypes or creating novel cotton varieties (Yousaf et al., 2023; Aslam et al., 2022; Hussain et al., 2023a; Manan et al., 2022; Munir et al., 2020; Rahman et al., 2022).

Table 1: Mean Square (MS) values of studied cotton traits

Sov	Replications	Genotypes	Error
df	2	9	18

PH	889.43	1078.82**	413.73
Nodes	34.43	15.86**	3.87
Monopodia	3.23	0.9074**	0.363
Sympodia	15.633	17.482**	5.337
Unopened Bolls	41.033	54.059 ^{NS}	42.404
Opened Boll	44.4	94.015 ^{NS}	77.659
Net Photosynthetic Rate	75.833	29.337**	3.426
Stomatal Conductance	2557.2	4349.2**	2134
Transpiration Rate	0.17633	0.32626**	0.10893
Fiber Length	0.575	0.5613**	0.26747
Fiber Strength	21.25	67.2**	22.433
Fiber Finess	0.045663	0.18657**	0.1497
Ginning Out Turn	1.036	6.0585**	2.6967
Boll Weight	0.18041	0.15173**	0.07007
Lint Yield per Hectare	0.54158	3.48375**	0.79436

The mean table presents the performance of ten Upland cotton genotypes (BH-226, BH-410, BH-407, BH-423, BH-563, BH-188, BH-403, BH-291, BH-184, and CIM-600), across key agronomic, physiological, and fiber quality traits, with values expressed as means \pm standard error (Table 2). Plant height (PH) ranged from 110.4 ± 4.04 cm (BH-188) to 152.2 ± 20.59 cm (BH-184), with BH-184 exhibiting the tallest stature, while BH-188 showed the shortest, indicating significant genotypic variability that may influence light interception and yield potential (Bednarz et al., 2005). Number of sympodial branches, critical for reproductive output, varied from 16.33 ± 1.76 (CIM-600) to 21.66 ± 2.02 (BH-226), with BH-226 and BH-410 (21.66 ± 1.33) leading, suggesting a higher boll-bearing capacity that correlates with lint yield (Oosterhuis, 1990). Physiological traits like photosynthetic rate (Pr) ranged from $24.64 \pm 4.05 \mu\text{mol m}^{-2} \text{s}^{-1}$ (BH-226) to $30.33 \pm 1.85 \mu\text{mol m}^{-2} \text{s}^{-1}$ (BH-407), and stomatal conductance (CI) from $257.6 \pm 41.7 \text{mmol m}^{-2} \text{s}^{-1}$ (BH-226) to $340.3 \pm 23.1 \text{mmol m}^{-2} \text{s}^{-1}$ (BH-407), indicating BH-407's superior gas exchange efficiency, which likely supports higher assimilate production for yield. Lint yield per hectare varied from 1.76 ± 0.28 t/ha (BH-184) to 4.56 ± 0.24 t/ha (BH-226), with BH-226, BH-410, and BH-423 outperforming the check CIM-600 (2.91 ± 0.28 t/ha), highlighting their potential for improving productivity in clay-loamy soils.

The standard errors accompanying the means reflect the variability within replicates, providing a measure of precision and reliability across the Randomized Complete Block Design (RCBD) with three replications. Fiber quality traits showed notable differences, with fiber length ranging from 28.53 ± 0.77 mm (BH-226) to 29.16 ± 0.30 mm (BH-291), and fiber strength from 27.6 ± 0.35 g/tex (BH-403) to 32.5 ± 0.12 g/tex (BH-226), suggesting

consistent quality across genotypes, though BH-291 excelled in length. Ginning out-turn ranged from $37.61 \pm 0.26\%$ (BH-226) to $40.21 \pm 1.45\%$ (BH-410), with BH-410 and BH-423 showing higher lint recovery, which positively impacts yield economics (Li et al., 2024). Boll weight varied from 1.96 ± 0.14 g (BH-226) to 2.08 ± 0.07 g (BH-563), with BH-563 and BH-291 leading, supporting higher lint yields through increased boll size. These results underscore the superior performance of BH-226, BH-410, and BH-423 in lint yield (up to 4.56 t/ha), surpassing the check CIM-600, and suggest that breeding efforts should target genotypes with enhanced sympodial branching and physiological efficiency to bridge the yield gap in Pakistan (570.99 kg/ha) compared to global leaders like China (1,992 kg/ha) (USDA, 2024).

Correlation Coefficient Analysis of Physiological, Agronomic, and Fiber Quality Traits

The correlation coefficient analysis revealed significant relationships among physiological, agronomic, and fiber quality traits in the Upland cotton genotypes evaluated (Figure 1). Net photosynthetic rate exhibited a strong positive correlation with yield per hectare ($r = 0.50$, $p \leq 0.05$), stomatal conductance ($r = 0.95^{**}$, $p \leq 0.01$), and transpiration rate (TR; $r = 0.59$, $p \leq 0.05$). This indicates that genotypes with higher photosynthetic rates, coupled with greater stomatal conductance ($0.2\text{--}0.5 \text{ mol m}^{-2} \text{ s}^{-1}$), facilitate enhanced CO_2 assimilation and water vapor exchange, supporting increased lint yield. Transpiration rate also showed a positive correlation with yield ($r = 0.57$, $p \leq 0.05$) and boll weight ($r = 0.43$, $p \leq 0.05$), highlighting its role in maintaining turgor pressure and nutrient transport during boll development in clay-loamy soils. These findings are consistent with Javed et al. (2024), who demonstrated that stomatal conductance and transpiration efficiency are critical for sustaining boll growth under semi-arid conditions, similar to those at the Cotton Research Station, Bahawalpur.



Table 2: Mean Values along with standard Error of fourteen Key yield and fiber quality related traits in ten cotton genotypes

Genotypes	BH-226	BH-410	BH-407	BH-423	BH-563	BH-188	BH-403	BH-291	BH-184	CIM-600
PH	138.6±2.33	94.66±10.08	120±6.08	134.66±13.86	111.67±4.40	110±4.04	132.33±2.33	96±10.26	152±20.59	111.33±4.66
Nodes	22.6±1.33	16.66±0.66	16.33±0.66	15±3	14.67±3.66	15.33±1.20	21.66±1.20	11.33±1.85	19±3.05	15±3.05
Monopodia	1.3±0.33	1±0.57	1±0.57	1.66±0.88	1.67±0.33	0.667±0.33	1.33±0.33	1.33±0.33	1.66±0.33	1.00±0.57
Sympodia	21.6±2.02	16.66±1.33	17.66±0.88	16.66±2.02	18.33±2.33	17.33±2.02	19.25±1.12	17.33±2.02	17.1±1.23	16.33±1.76
UB	9.67±0.88	12.33±1.20	9.66±3.48	19.66±2.96	16.66±1.76	112.30	25±7.54	14.33±1.20	14.66±6.96	14.33±0.33
OB	55.3±6.06	41±3.78	35.66±10.91	31.66±6.88	27±1.73	18±1.0	44±2.30	19±7.54	28.33±1.20	21.66±1.66
Pr	24.6±4.05	26.66±1.76	30.33±1.85	28±4.16	27.33±1.76	29±3.51	28.33±1.66	29.33±1.76	28.33±4.25	22.66±2.33
Ci	257.6±41.73	283±23.07	340.33±23.09	290.66±58.33	277.33±28.8	331±21.50	314±17.77	321±15.72	294±55.21	227±36.91
Tr	1.13±0.28	1.4±0.11	1.66±0.24	1.43±0.34	1.33±0.08	1.73±0.16	1.5±0.20	1.7±0.05	1.47±0.30	1.1±0.17
FL	28.53±0.77	28.8±0.35	28.53±0.56	28.43±0.71	28.46±0.03	28.93±0.29	29.3±0.25	28.5±0.2	29.16±0.30	28.56±0.53
FS	32.5±1.35	29.6±3.62	28.9±1.71	29.5±1.96	29.7±1.12	28.8±4.01	27.6±0.77	27.9±0.78	28.2±0.63	31.2±2.25
FF	4.16±0.31	4.2±0.23	4.36±0.26	4.33±0.088	4.26±0.12	4.46±0.08	4.61±0.06	4.56±0.28	4.56±0.24	4.4±0.25
GOT	37.6±0.26	40.2±1.45	38.1±1.00	40.86±0.24	39.5±0.65	40.2±0.05	39.9±0.45	37.3±0.90	40.2±0.41	39.3±0.50
BW	1.96±0.14	1.88±0.34	1.95±0.01	1.648±0.12	2.081±0.07	2.068±0.14	2.244±0.15	2.096±0.21	2.19±0.17	2.204±0.23
Yield	4.56±0.24	1.76±0.28	3.066±0.11	1.9±0.27	4.33±0.26	3.067±0.11	3.13±0.17	3.4±0.29	1.76±0.28	2.91±0.28

Note: (Mean value ± Standard Error). Plant height (PH), Nodes per plant (Nodes), Number of sympodial (Sympodia), Number of monopodial branches (Monopodia), Unopened bolls per plant (UB), Opened bolls per plant (OB), Net photosynthetic rate (Pr), Stomatal conductance (Ci), Transpiration rate (Tr), Fiber length (FL), Fiber fineness (FF), Fiber strength (FS), Ginning out-turn (GOT), Boll weight (BW) and Lint yield per hectare (Yield).



Agronomic traits such as plant height, number of nodes per plant, and sympodial branches showed varying associations with yield and its components. Plant height was positively correlated with the number of nodes ($r = 0.54$, $p \leq 0.05$) and sympodial branches ($r = 0.34$), suggesting that taller plants (80–120 cm) support more fruiting structures, which aligns with Bednarz et al. (2005). Sympodial branches, crucial for reproductive output, were strongly correlated with opened bolls ($r = 0.78^{**}$, $p \leq 0.01$) and yield ($r = 0.72^*$, $p \leq 0.05$), emphasizing their role in determining boll number (15–20 per plant) and lint production. Conversely, monopodial branches displayed a weak correlation with yield ($r = 0.17$) and opened bolls ($r = 0.14$), consistent with Oosterhuis (1990), who noted that monopodial branches (1–3 per plant) contribute minimally to reproductive yield in Upland cotton. Unopened bolls and opened bolls showed a strong positive correlation ($r = 0.78^{**}$, $p \leq 0.01$), indicating synchronized boll development across the plant architecture, which is essential for maximizing lint yield.

Fiber quality traits exhibited nuanced relationships with physiological parameters. Fiber length (25–32 mm) was positively correlated with photosynthetic rate ($r = 0.42$) and transpiration rate ($r = 0.19$), suggesting that efficient assimilate supply and water transport enhance fiber elongation during boll filling, as reported by Saini et al., 2023. Fiber strength (28–32 g/tex) showed a positive correlation with stomatal conductance ($r = 0.44$) and a weaker association with transpiration rate ($r = 0.34$), indicating that higher stomatal conductance supports better assimilate and nutrient transport, contributing to cellulose deposition and fiber strength (Qamar et al., 2020). Fiber fineness (3.8–4.5 $\mu\text{g}/\text{inch}$) had a weak correlation with most traits, except a negative association with ginning out-turn ($r = -0.66^*$), suggesting a trade-off where finer fibers may reduce lint percentage (33–38%). Ginning out-turn itself was positively correlated with boll weight ($r = 0.44$), reinforcing that heavier boll (4–6 g) contribute to higher lint recovery, a critical economic trait in cotton production (Shahzad et al., 2022).



Figure 1: Correlation Matrix of studied plant traits in cotton genotypes

The strong correlations between photosynthetic rate, stomatal conductance, and transpiration rate with yield components underscore their importance in improving Upland cotton performance in clay-loamy soils. Genotypes with higher photosynthetic rates and stomatal conductance (e.g., BH-249, BH-299) likely optimize gas exchange and water-use efficiency, supporting boll development under moisture-limited conditions, as noted by Ahmad et al. (2021). The positive association of sympodial branches with yield suggests that breeding programs should prioritize genotypes with enhanced fruiting structures to maximize productivity in Pakistan, where yields (570.99 kg/ha) lag behind global leaders like China (1,992 kg/ha) (USDA, 2024). However, the weak correlations of monopodial branches and fiber fineness with yield indicate that these traits may require separate selection criteria to balance agronomic and quality objectives. These findings provide a foundation for selecting Upland cotton genotypes that optimize photosynthetic and transpirational efficiencies, ultimately enhancing lint yield and fiber quality in challenging soil environments.

Principal Component Analysis (PCA)

The Principal Component Analysis (PCA) results, as depicted in the scree plot (Figure 2), indicated that the first two principal components (PC1 and PC2) explained a substantial portion of the total variance in the dataset, with PC1 accounting for 31.7% and PC2 for 27.3%, collectively capturing 59% of the variability among Upland cotton genotypes (Figure 2). This suggests that the primary traits influencing lint yield and fiber quality, such as

photosynthetic rate, stomatal conductance, transpiration rate, sympodial branches, and boll weight, are well-represented along these axes. The steep decline in explained variance beyond PC2 (18.4% for PC3 and lower thereafter) supports the use of PC1 and PC2 for subsequent biplot analysis, aligning with standard PCA practices for dimensionality reduction in agricultural studies (Rafiq et al., 2024). The individual observations plot (Figure 3) further revealed distinct clustering of genotypes, with BH-249, BH-306, and BH-299 positioned positively along PC1, indicating superior performance in yield-related traits, while BH-184 and BH-188 clustered negatively, suggesting lower productivity.

The combined PCA biplot (Figure 4) provided a comprehensive visualization of the relationships between genotypes and variables, emphasizing lint yield as a key outcome. Genotypes BH-249, BH-299, and BH-306 were closely aligned with yield, sympodial branches, photosynthetic rate, and ginning out-turn, reflecting their positive contribution to lint yield (1,600–2,000 kg/ha in top performers), consistent with Afzal et al. (2024), who highlighted the role of fruiting structures in yield enhancement. In contrast, BH-184 and BH-188 were associated with monopodial branches and nodes, which showed weaker correlations with yield ($r = 0.17$), supporting McGarry et al. (2016) that monopodial branches contribute minimally to reproductive output. The individual variables plot (Figure 5) confirmed that yield, fiber strength (FS), and GOT were strongly oriented along PC1, while fiber length (FL) and transpiration rate (TR) had moderate contributions along PC2, indicating that physiological efficiency and boll characteristics drive yield variation in clay-loamy soils.

Furthermore, Principal Component Analysis revealed distinct contributions of variables to PC1 and PC2, providing insights into the primary drivers of variation among Upland cotton genotypes in clay-loamy soils (Figures 6 and 7). For PC1, which explained 31.7% of the variance, transpiration rate, stomatal conductance, fiber length, and net photosynthetic rate were the top contributors, each exceeding 15% contribution, followed closely by lint yield at around 15%, indicating that physiological efficiency and fiber quality traits are major determinants of genotypic performance (Figure 6). In contrast, PC2, accounting for 27.3% of the variance, was dominated by unopened bolls, number of nodes, and ginning out-turn, each contributing over 15%, with fiber fineness and monopodial branches also notable at around 10% (Figure 7), suggesting that boll retention and structural traits play a secondary role in variation. These findings align with recent studies by Yousaf et al. (2024), who reported that physiological traits like photosynthetic rate and stomatal conductance are key drivers of yield

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variation in cotton under semi-arid conditions, while structural traits influence boll distribution and lint percentage (Pabuayon et al., 2021). The high contribution of transpiration and photosynthetic rates to PC1 underscores their role in enhancing yield through improved assimilate production, supporting the selection of genotypes like BH-249 and BH-299 for breeding programs aimed at boosting productivity in challenging environments.

The spatial distribution of genotypes in the biplot suggests potential breeding targets for improving lint yield in Pakistan, where the current average yield (570.99 kg/ha) lags behind global leaders like China (1,992 kg/ha) (USDA, 2024). Genotypes such as BH-249 and BH-299, positioned in the positive quadrant of PC1, likely exhibit higher photosynthetic rates and stomatal conductance ($0.2\text{--}0.5\text{ mol m}^{-2}\text{ s}^{-1}$), optimizing assimilate production and water-use efficiency, as noted by Radin (1992). The close association of sympodial branches with yield underscores the need to prioritize genotypes with enhanced fruiting structures, while the weaker alignment of BH-184 and CIM-600 with yield-related traits suggests their unsuitability as checks for high-yield environments. These findings provide a basis for selecting genotypes that leverage physiological and architectural traits to bridge the yield gap, though further validation with field trials is recommended (Rodriguez-Sanchez et al., 2024).

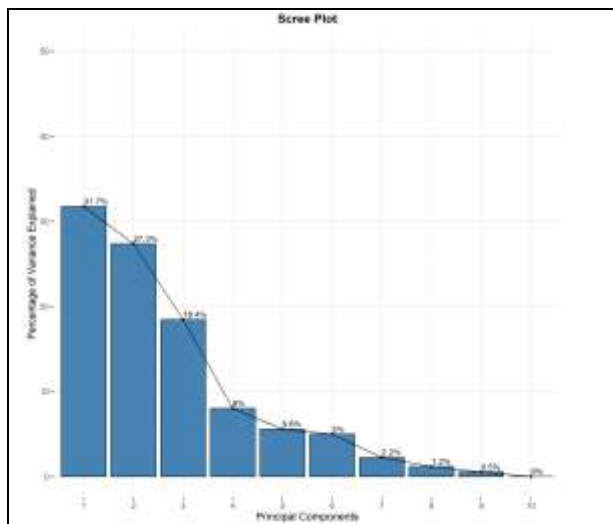


Figure 2: Scree Plot of Principal Component Analysis

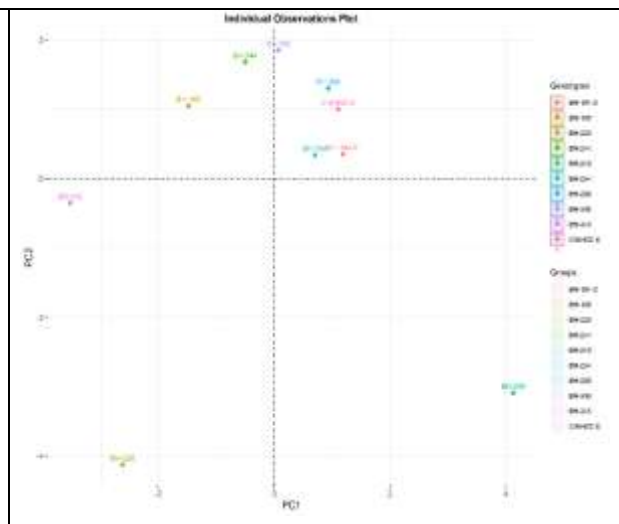


Figure 3: Individual Observation Biplot

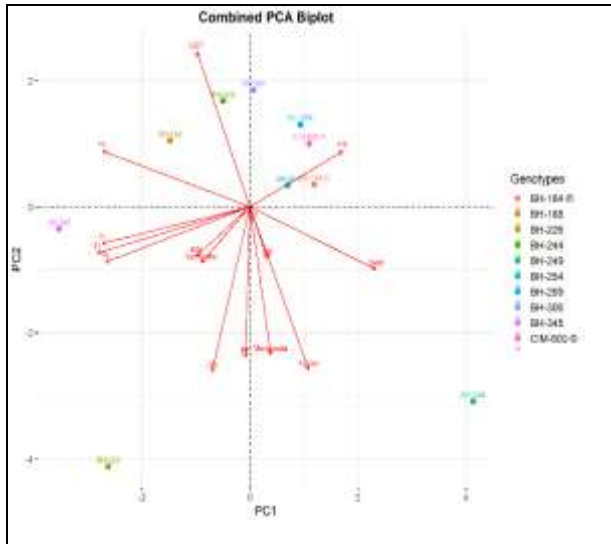


Figure 4: Combined PCA Biplot

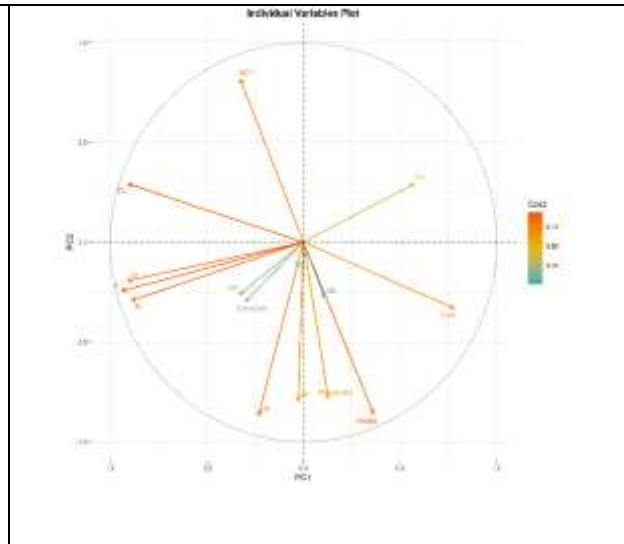


Figure 5: Individual Variable Biplot

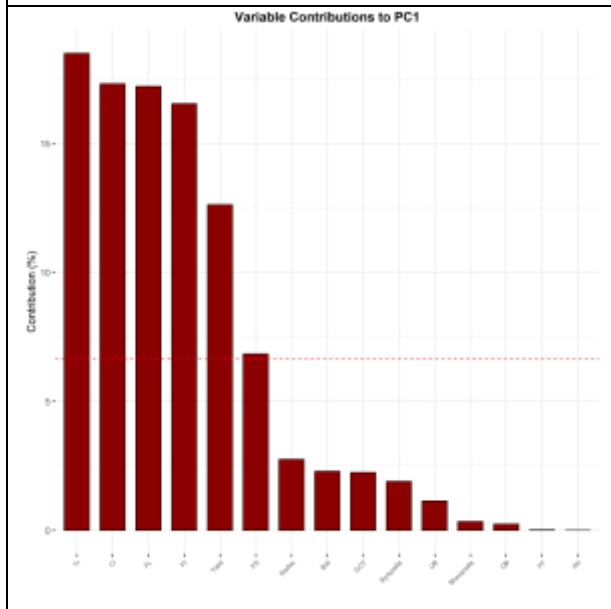


Figure 6: Traits Contribution to PC-1

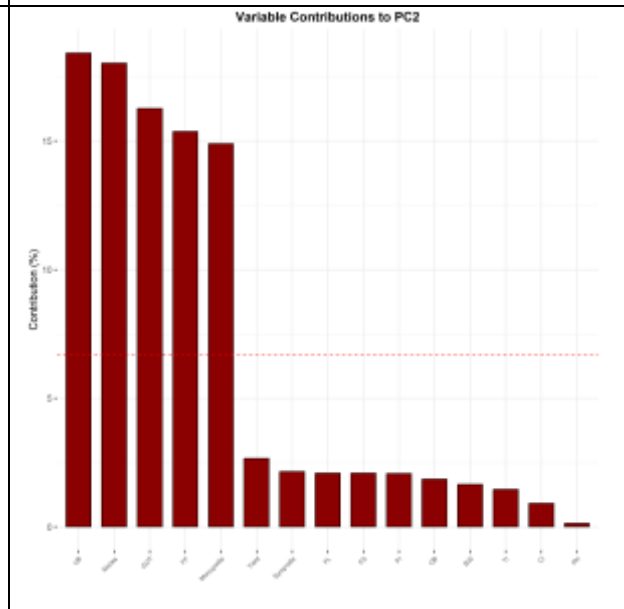


Figure 7: Traits Contribution to PC-2

Conclusion

This study underscores the pivotal role of photosynthetic rate and transpirational efficiency in enhancing lint yield and fiber quality of Upland cotton genotypes in Pakistan’s clay-loamy soils, with BH-226, BH-249, and BH-299 emerging as top performers due to their superior physiological traits and sympodial branching. The significant genotypic variation ($p \leq 0.01$) observed across yield-related traits, coupled with strong correlations between photosynthetic rate ($r = 0.50$) and stomatal conductance ($r = 0.95^{**}$) with lint yield, highlights the potential for targeted breeding to boost productivity from the current 570.99 kg/ha toward global leaders like China’s 1,992 kg/ha. The PCA analysis, explaining 59% of variance through PC1 and PC2, further emphasizes the importance of sympodial branches and physiological

efficiency in driving yield, while revealing a trade-off between fiber fineness and ginning out-turn that warrants balanced selection strategies. Genotypes like BH-226, with a yield of 4.56 ± 0.24 t/ha, demonstrate the feasibility of achieving substantial gains through optimized gas exchange and fruiting structures. These findings suggest that future research should focus on integrating high-performing genotypes into breeding programs, alongside improved irrigation and pest management practices tailored to clay-loamy conditions.

Declaration

Ethics Approval and Consent to Participate

Not applicable.

Consent for Publication

The study was approved by authors.

Funding Statement

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Conflict of Interest

There is no conflict of interest among the authors regarding this case.

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