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Research Article

Performance Evaluation and Stress Screening of Colored Cotton Genotypes for Yield, Fiber Quality and Drought Tolerance

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ABSTRACT

Naturally colored cotton (*Gossypium hirsutum* L.) offers an eco-friendly alternative to conventional white cotton by reducing the need for synthetic dyes. However, its cultivation remains limited due to lower yield and suboptimal fiber quality, particularly under drought stress. We evaluated the genetic and physiological performance of 20 white and naturally colored cotton genotypes under normal and water-deficit conditions using field trials (RCBD) and laboratory PEG (polyethylene glycol)-6000 screening (CRD). Agronomic, fiber quality and physiological traits were recorded, including plant height, bolls per plant, seed cotton yield, lint weight, fiber length and strength, chlorophyll content, photosynthetic rate and stomatal conductance. Significant genotypic variability was observed for most traits. Drought reduced yield and fiber strength most markedly in green-colored genotypes, whereas Light Brown and Khaki American A maintained higher photosynthetic rates, chlorophyll content and yield stability under limited irrigation. Path coefficient analysis identified lint weight, boll weight and fiber length as key contributors to seed cotton yield. These findings demonstrate that integrating genetic selection with physiological screening (field + PEG assays) can accelerate breeding of drought-resilient colored cotton, offering practical value to breeders and the textile industry in water-limited regions.

Keywords: Colored cotton, drought stress, fiber quality, yield traits, path coefficient analysis, physiological response, sustainable breeding.

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INTRODUCTION

Cotton (*Gossypium hirsutum* L.) remains a cornerstone of the global textile industry and a vital component of Pakistan's economy, contributing significantly to agricultural GDP and employment. In recent years, increasing demand for environmentally friendly textiles has spurred interest in naturally colored cotton (NCC), which eliminates the need for harmful synthetic dyes. Colored cotton genotypes, producing fibers in brown, green, and khaki shades, offer a sustainable alternative to conventional white cotton. However, the commercial adoption of NCC remains limited due to lower yield potential, reduced fiber quality, and sensitivity to abiotic stresses, particularly drought.

Drought is one of the most critical environmental stresses affecting cotton growth, fiber development, and ultimately, productivity. The situation is aggravated by climate change, irregular rainfall, and limited irrigation resources in major cotton-growing regions, including Pakistan. In such conditions, cotton plants exhibit reduced boll formation, fiber elongation, photosynthesis, and nutrient translocation. Naturally colored genotypes, often developed from wild or unadapted sources, are even more vulnerable due to their limited selection history for stress adaptation. Despite their limitations, colored cotton genotypes hold untapped genetic potential. Some possess tolerance to pests, diseases, and abiotic stress, and exhibit natural resistance to UV radiation and pathogens. Recent advances in cotton breeding and molecular techniques offer opportunities to enhance both yield and fiber quality traits in NCC, especially through selection based on genetic variability, correlation analysis, and stress physiology.

Previous studies have either focused on the genetic evaluation of colored cotton under optimal conditions or their physiological response to water deficit, but rarely both. To bridge this gap, this study combines field evaluation and drought screening to comprehensively assess yield potential, fiber traits, and physiological responses of white and colored cotton genotypes under normal and drought stress conditions.

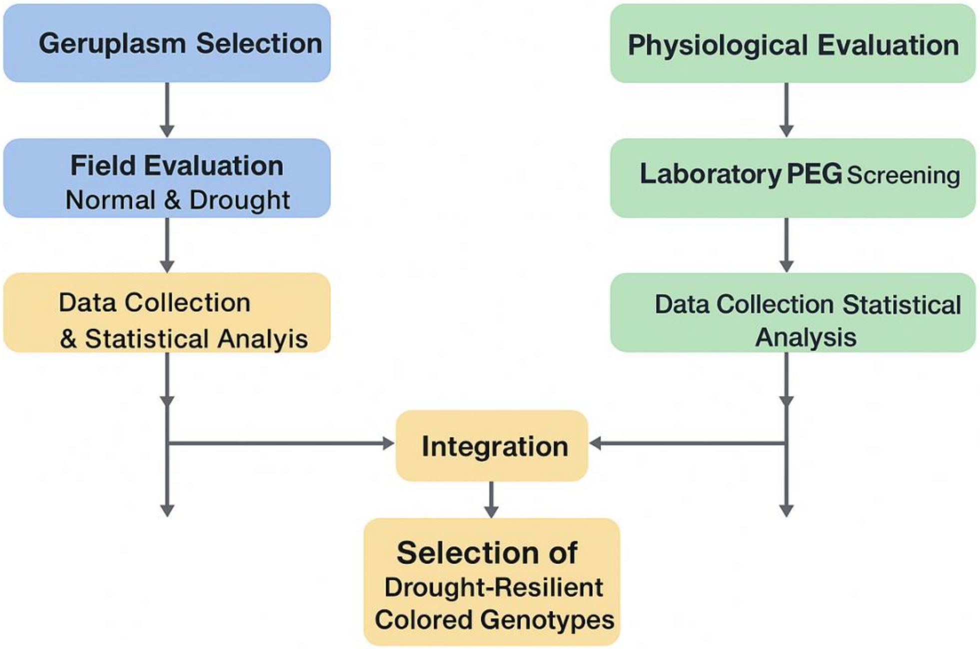

Figure 1. Conceptual framework showing the genetic and physiological evaluation workflow for identifying drought resilient colored cotton genotypes.

Objectives of Study

To assess genetic variability among colored cotton genotypes for key morphological and fiber quality traits.

To evaluate the physiological and agronomic performance of selected genotypes under water-deficit conditions.

To identify promising genotypes for future breeding programs targeting colored, drought-resilient cotton.

MATERIALS AND METHODS

Experimental Site and Germplasm

Two separate but complementary experiments were conducted at the MNS University of Agriculture, Multan, located in the cotton-growing region of southern Punjab, Pakistan.

Table 1. List of Cotton Genotypes Used in the Study

Genotype ID	Type	Color Shade	Source/Origin
FH-118	White	—	Public Sector
MNH-1026	White	—	Public Sector
Light Brown	Colored	Light Brown	Collected Germplasm
Dark Brown	Colored	Dark Brown	Collected Germplasm
Khaki American A	Colored	Khaki	Imported
Khaki American B	Colored	Khaki	Imported
Light Green	Colored	Light Green	Local Collection

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Dark Green	Colored	Dark Green	Local Collection
D-Brown	Colored	Deep Brown	Local Collection
L-Brown	Colored	Light Brown (variant)	Local Collection

A total of 20 cotton genotypes, including white and naturally colored lines (light brown, dark brown, green, khaki American A & B, etc.), were used for both field and lab evaluations. These genotypes were sourced from public breeding programs and private institutions with the aim of assessing both genetic potential and drought resilience (Table 1).

Soil and Climatic Conditions

The field experiments were conducted on a silty-clay loam soil, pH 7.6; organic matter 0.8%; available water holding capacity 22%. The experimental area lies in a semi-arid zone: mean growing-season (May–September) maximum temperature 34–38 °C, minimum 22–26 °C, and cumulative rainfall during the season ~120–160 mm (based on local meteorological station data for the study year). Irrigation water was supplied via furrow irrigation as described below.

Experimental Design

Field Experiment under Normal and Drought Conditions

The field trial was laid out in a Randomized Complete Block Design (RCBD) with three replications and two irrigation treatments:

T1: Normal irrigation (control)
T2: Limited irrigation (drought stress imposed after flowering)

Each genotype was sown in 3-meter-long rows with row-to-row spacing of 75 cm and plant-to-plant spacing of 25 cm. Recommended agronomic practices were followed for fertilization, pest management, and weeding.

The limited irrigation treatment (T2) consisted of withholding supplemental irrigation for 30 days starting at first flower initiation (early reproductive stage) to impose reproductive-phase water stress, which is known to critically impact boll development and final yield.

PEG-Mediated Drought Stress (Laboratory Screening)

To simulate drought stress in a controlled environment, a polyethylene glycol (PEG-6000) solution was used. Seeds of selected colored cotton genotypes were germinated in petri dishes treated with:

Control (0% PEG)
Moderate stress (10% PEG)
Severe stress (20% PEG)

The experiment was conducted in a Completely Randomized Design (CRD) with two replicates per treatment.

Laboratory osmotic stress was induced using polyethylene glycol (PEG-6000) solutions adjusted to approximate osmotic potentials of –0.3 MPa (10% w/v), –0.6 MPa (15% w/v), and –0.9 MPa (20% w/v) following Xiao et al. (2020). Seeds were surface-sterilized and placed in Petri dishes with filter paper moistened with the respective PEG solution, incubated at 25 ± 2 °C for 7 days. Each PEG level and control (0% PEG) had three replicates, with 25 seeds per replicate. Germination percentage, root and shoot length and fresh/dry biomass were recorded at day 7.

Table 2. Description of Drought Treatments and PEG Concentrations

Genotype	**Bolls/Plant**	**Boll Weight (g)**	**Lint Weight (g)**	**Seed Cotton Yield (g)**	**Fiber Length (inch)**	**Fiber Strength (g/tex)**
FH-118	19.5	4.1	7.8	18.3	1.12	27.2
MNH-1026	18.3	3.9	7.4	17.2	1.1	26.5
Light Brown	16.2	3.5	6.2	15.4	1.03	24.8
Khaki A	15.9	3.6	6.5	15.9	1.05	25
Dark Green	12.7	2.9	5.1	12.2	0.96	21.3
Light Green	11.4	2.8	4.9	11.5	0.93	20.7

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Data Collection

Morphological and Agronomic Traits

Table 3. Lab experiments, the following traits were recorded

Trait	Units	Description
Plant height	cm	From soil surface to main stem tip
Monopodial branches	number	Non-fruiting branches
Sympodial branches	number	Fruiting branches
Number of bolls	number/plant	Total bolls per plant
Boll weight	g	Average weight of mature bolls
Seed weight	g	Total seed mass per plant
Lint weight	g	Ginned fiber weight per plant
Seed cotton yield	g	Total unginned cotton yield
Seed index	%	(100-seed weight)
GOT (Ginning Out Turn)	%	Lint weight / seed cotton yield × 100

Fiber Quality Traits

Fiber traits were measured using High Volume Instrument (HVI) and included:
Fiber length (inches)
Fiber strength (g/tex)
Fiber uniformity (%)
Micronaire value (µg/inch)

Physiological Parameters (Field Only)

The following parameters were recorded under both irrigation conditions using portable instruments:
Photosynthetic rate (µmol CO_2 m^{-2} s^{-1})
Transpiration rate (mmol H_2O m^{-2} s^{-1})
Stomatal conductance (mol H_2O m^{-2} s^{-1})
Chlorophyll content (SPAD units)

Drought Stress Indices (Lab)

In the PEG-mediated screening, the following drought-related traits were evaluated:
Germination percentage (%)
Root and shoot length (cm)
Fresh and dry weight of root and shoot (g)

Statistical Analysis

In field trials, data were recorded from five randomly selected plants per plot and means per plot used for ANOVA.
Data were subjected to Analysis of Variance (ANOVA) to detect significant differences among genotypes and treatments. Genotypic and phenotypic correlation coefficients were computed to assess interrelationships among traits.
All statistical analyses were conducted using Statistix 8.1, SPSS 20, and MS Excel 2016.
Path coefficient analysis was applied to identify direct and indirect effects of traits on seed cotton yield.
Principal Component Analysis (PCA) was used to identify key traits contributing to variation under normal and stress conditions.
Stress tolerance indices (e.g., STI, SSI, MP, TOL) were computed for lab-based drought screening.
For lab assays mean values were computed per replicate (n = 3). Stress tolerance indices were calculated following standard formulas:
Stress Tolerance Index (STI) = (Yp × Ys)/ (Yp^2_mean),
Mean Productivity (MP) = (Yp + Ys)/2,
Stress Susceptibility Index (SSI) = [1 − (Ys/Yp)] / SI where Yp and Ys are yield of genotypes under control and stress respectively, and
SI = 1 − (mean Ys/mean Yp) (Fernandez, 1992; Blum, 2011).

RESULTS

Performance of Genotypes under Normal Field Conditions

Morphological and Yield Traits

Analysis of variance (ANOVA) under normal irrigation revealed **significant genotypic differences** for most morphological and yield traits, including number of bolls per plant, boll weight, lint weight, seed cotton yield, seed index, and ginning out turn (GOT). Traits such as internodal distance and number of monopodial branches were non-significant across genotypes. Mean performance of genotypes for yield and fiber traits under normal irrigation is presented in Table 3.

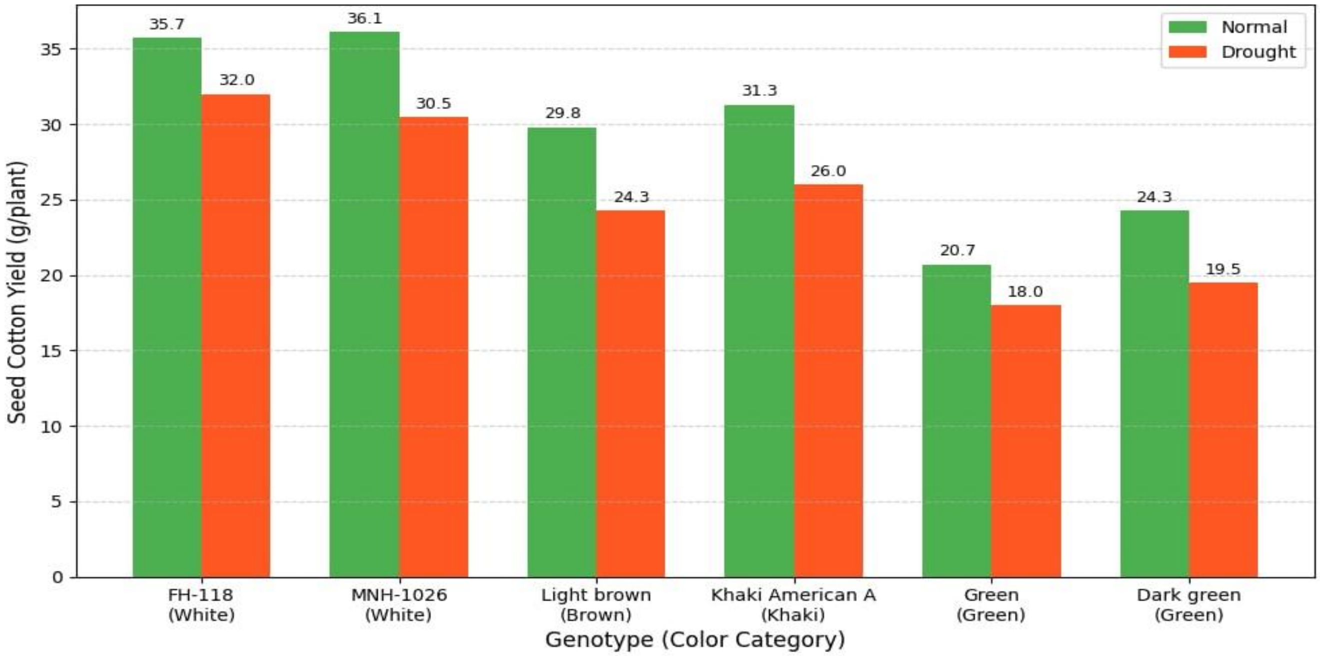

Figure 2. Comparison of seed cotton yield under normal and drought stress conditions.

Table 3. Mean Performance of Cotton Genotypes under Normal Conditions

Genotype	Plant Height (cm)	Bolls/ Plant	Boll Weight (g)	Lint Weight (g/plant)	Seed Cotton Yield (g/plant)	GOT (%)	Seed Index (g)	Fiber Length (inch)	Fiber Strength (g/tex)	Micronaire (µg/inch)
FH-118 (White)	112.4	19.5	4.1	7.8	18.3	38.2	8.5	1.12	27.2	4.1
MNH-1026 (White)	108.6	18.3	3.9	7.4	17.2	37.8	8.3	1.1	26.5	4.3
Light Brown	104.2	16.2	3.5	6.2	15.4	36.4	8.1	1.03	24.8	4.2
Khaki American A	106.3	15.9	3.6	6.5	15.9	36.9	8.2	1.05	25	4.4
Khaki American B	102.8	15.4	3.3	6.1	14.8	35.8	8	1.02	24.5	4.3
Dark Brown	100.5	14.7	3.2	5.8	14.2	35.2	7.9	1	23.8	4.1
Light Green	96.4	11.4	2.8	4.9	11.5	33.6	7.6	0.93	20.7	3.9

Dark Green	98.2	12.7	2.9	5.1	12.2	34.2	7.7	0.96	21.3	4
D-Brown (Local)	101.8	14.5	3.1	5.6	13.9	35	7.8	0.98	22.4	4.2
L-Brown (Variant)	103.5	15	3.3	5.9	14.7	35.4	8	1.01	23	4.3
Mean	103.5	15.6	3.4	6.1	14.8	36.2	8	1.02	23.9	4.2

Significant variation was observed among genotypes. White genotypes (FH-118, MNH-1026) recorded the highest seed cotton yield and fiber quality, while light brown and khaki genotypes exhibited moderate but stable performance.

Fiber Quality Traits

Significant variation ($p < 0.01$) was observed in:

Fiber length (ranged from 0.85 to 1.12 inches)

Fiber strength (18.5 to 27.2 g/tex)

Micronaire value (3.7 to 4.8 µg/inch)

Fiber uniformity (78–87%)

White genotypes recorded the highest fiber length and strength. Notably, khaki American B and light brown colored genotypes had fiber strength values comparable to those of white genotypes, suggesting potential for breeding.

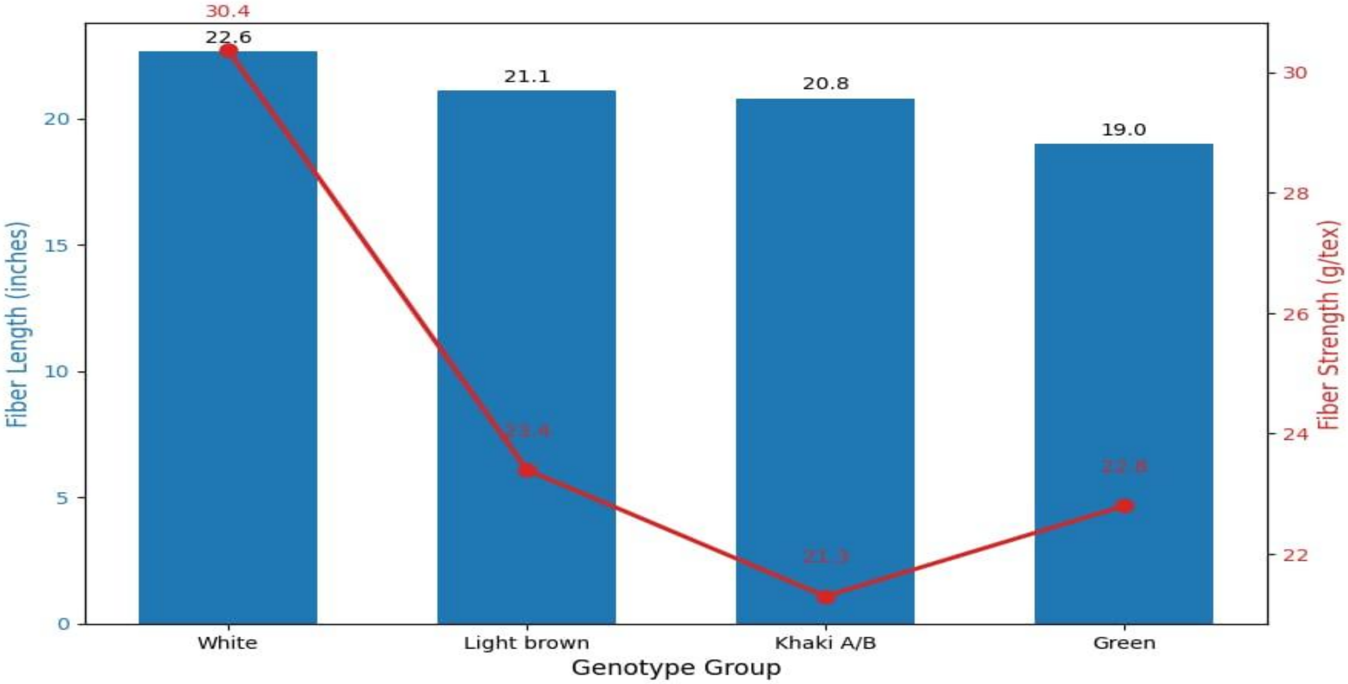

Figure 3. Fiber Length and Strength Comparison among Genotypes.

Correlation and Path Analysis

The genotypic and phenotypic correlation coefficients among yield and fiber quality traits are presented in Figure 3. Correlation analysis revealed that:

Boll weight, lint weight, and seed index were positively and significantly correlated with seed cotton yield.

Fiber strength and length showed significant positive correlations with yield components, especially lint weight and GOT, indicating that simultaneous improvement in yield and fiber quality is feasible.

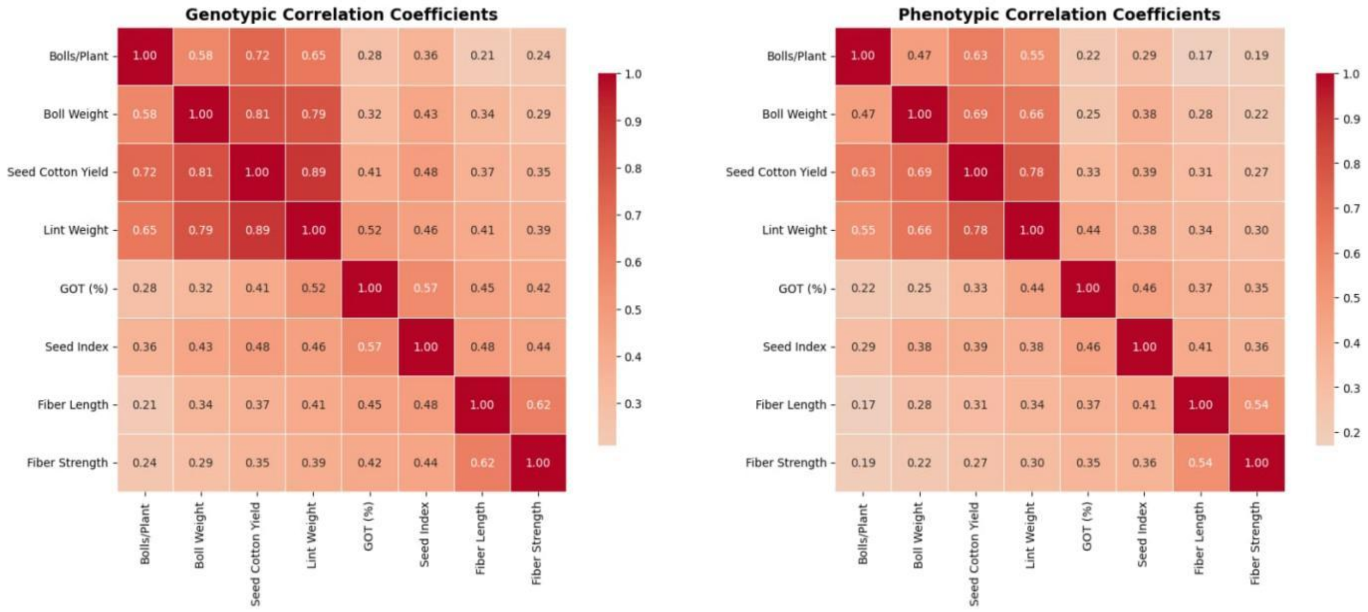

Figure 4. Genotypic and Phenotypic Correlation Coefficients: Figure 3. Photosynthetic rate (μmol CO_2 m^{-2} s^{-1}) and chlorophyll content (SPAD units) of selected genotypes under normal and drought conditions. Error bars represent standard error of the mean (n = 5 plants per plot). Treatments: Control = normal irrigation; Drought = limited irrigation (30 days withheld at flowering).

To further clarify the interrelationships among traits, path coefficient analysis was performed (Table 5). Lint weight and boll weight exhibited the highest direct effects on seed cotton yield, suggesting that they are the most influential yield components in colored cotton breeding.

Lint weight (0.423) and boll weight (0.386) had the highest direct effects on seed cotton yield.

Seed index also exhibited a moderate positive direct effect (0.298), suggesting its reliability as a secondary selection criterion.

Fiber length and strength contributed indirectly via lint weight and boll weight, reflecting their indirect role in determining yield.

These results collectively indicate that selection for heavier bolls, higher lint weight, and improved fiber traits can effectively enhance seed cotton yield.

Table 5. Path Coefficient Analysis for Seed Cotton Yield

Traits	**Direct Effect on Yield**	**Indirect via Bolls/Plant**	**Indirect via Boll Weight**	**Indirect via Lint Weight**	**Indirect via GOT (%)**	**Indirect via Seed Index**	**Indirect via Fiber Length**	**Indirect via Fiber Strength**	**Total Correlation with Yield**
Bolls/Plant	0.215	—	0.122	0.138	0.041	0.056	0.033	0.029	0.72
Boll Weight	0.386	0.125	—	0.18	0.052	0.071	0.049	0.037	0.81
Lint Weight	0.423	0.14	0.183	—	0.06	0.078	0.053	0.041	0.89
GOT (%)	0.172	0.056	0.058	0.069	—	0.083	0.048	0.038	0.41
Seed Index	0.298	0.077	0.082	0.091	0.067	—	0.052	0.041	0.48
Fiber Length	0.164	0.045	0.052	0.066	0.048	0.057	—	0.055	0.37
Fiber Strength	0.153	0.04	0.044	0.059	0.042	0.05	0.062	—	0.35

Performance of Genotypes under Drought Stress

Field Evaluation under Limited Irrigation

Mean performance of cotton genotypes under drought stress conditions is presented in Table 6. Water deficit stress imposed during the reproductive phase significantly reduced performance across all measured traits:

Reduction in boll number, boll weight, seed cotton yield, and fiber strength was more pronounced in green and dark green genotypes.

Light brown and khaki American A genotypes maintained relatively better performance under drought, showing moderate reductions and maintaining yield stability.

White genotype FH-118 showed the least reduction in yield and fiber traits, confirming its drought tolerance.

Table 6. Mean Performance of Genotypes under Drought Stress

Genotype	**Plant Height (cm)**	**Bolls /Plant**	**Boll Weight (g)**	**Lint Weight (g/plant)**	**Seed Cotton Yield (g/plant)**	**GOT (%)**	**Seed Index (g)**	**Fiber Length (inch)**	**Fiber Strength (g/tex)**	**Micronaire (µg/inch)**
FH-118 (White)	101.3	17.8	3.8	6.8	16.1	37.1	8.3	1.1	26	4.2
MNH-1026 (White)	98.5	16.7	3.6	6.5	15	36.7	8.1	1.08	25.3	4.3
Light Brown	93.8	15.1	3.3	5.9	13.8	35.4	7.9	1.02	24.2	4.2
Khaki American A	95.6	15.6	3.4	6	14.3	35.9	8	1.04	24.5	4.3
Khaki American B	92.7	14.9	3.2	5.6	13.5	35	7.8	1	23.8	4.2
Dark Brown	90.2	13.7	3	5.3	12.9	34.6	7.7	0.97	23	4.1
Light Green	86.3	10.2	2.6	4.3	8.7	32.9	7.3	0.9	19.8	3.9
Dark Green	87.8	10.8	2.7	4.5	9.2	33.5	7.5	0.91	20.1	4
D-Brown (Local)	91.5	13.1	2.9	5	12.2	34.4	7.6	0.95	22.3	4.1
L-Brown (Variant)	92.6	13.8	3	5.2	12.8	34.7	7.8	0.97	22.8	4.1
Mean	93	14.2	3.2	5.5	12.9	35	7.8	0.99	23.2	4.1
LSD (0.05)	3.97	1.05	0.13	0.2	0.68	1.32	0.21	0.04	0.72	0.16

Physiological Responses under Stress

Significant reductions under drought were recorded in:

Photosynthetic rate (↓ 30–50%)

Stomatal conductance (↓ 40–60%)

Chlorophyll content (↓ 20–35%)

Transpiration rate (↓ 25–45%)

Colored genotypes such as light green and dark green exhibited the most drastic reductions, while light brown, khaki American A, and white genotypes (MNH-1026 and FH-118) showed more stable physiological traits under water stress.

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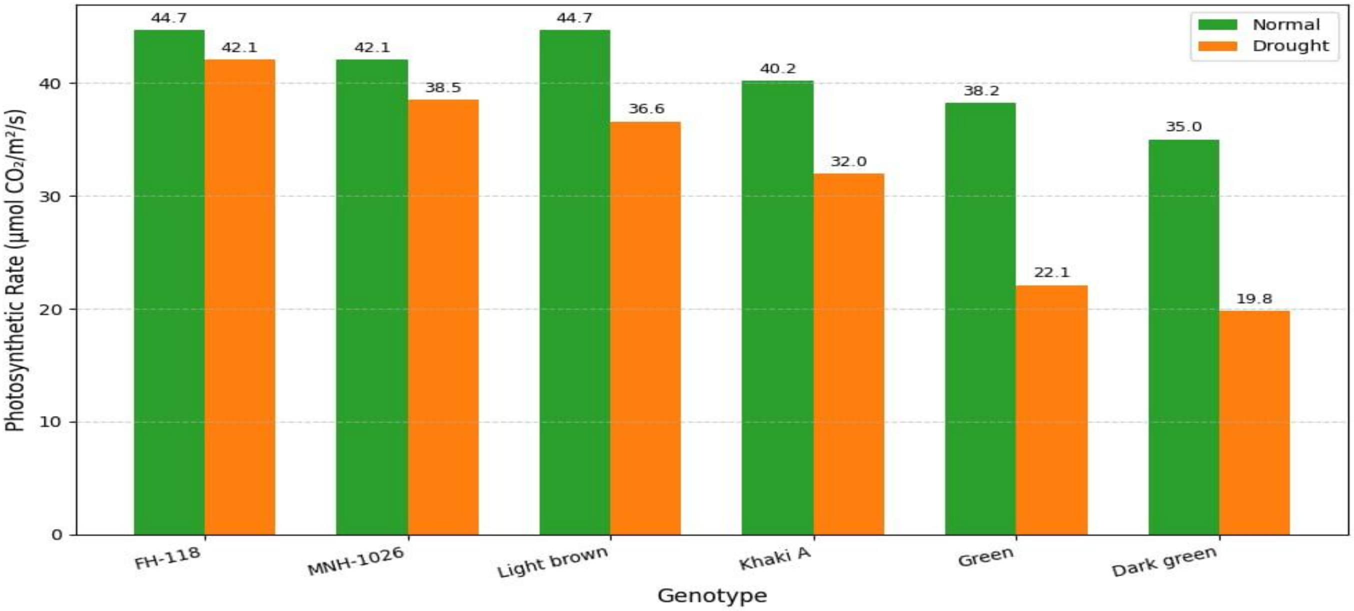

Figure 5. Physiological Traits under Normal and Drought Conditions.

PEG-Mediated Lab Screening

Physiological and laboratory-based drought tolerance indices are presented in Table 7.

Table 7. Physiological and PEG-based screening of cotton genotypes under drought stress: Values are means ± SE (n = 3). Photosynthetic rate in µmol CO_2 m^{-2} s^{-1}; stomatal conductance in mol H_2O m^{-2} s^{-1}; transpiration rate in mmol H_2O m^{-2} s^{-1}; Chlorophyll content (SPAD units); Germination (%) — percent. STI, SSI and MP are dimensionless indices. LSD (0.05) = Least Significant Difference at 5% probability.

Genotype	**Photosynthetic Rate (µmol CO_2 m^{-2} s^{-1})**	**Stomatal Conductance (mol H_2O m^{-2} s^{-1})**	**Transpiration Rate (mmol H_2O m^{-2} s^{-1})**	**Chlorophyll Content (SPAD units)**	**Germination (%)**	**Root Length (cm)**	**Shoot Length (cm)**	**Root /Shoot Ratio**	**STI**	**SSI**	**MP**
FH-118 (White)	15.8	0.34	3.9	41.2	91	10.8	8.4	1.29	0.89	0.68	0.87
MNH-1026 (White)	14.9	0.31	3.6	39.8	88	10.3	8.1	1.27	0.86	0.7	0.84
Light Brown	13.7	0.29	3.4	38.6	85	9.8	7.8	1.26	0.83	0.72	0.81
Khaki American A	13.9	0.3	3.5	39	87	10	7.9	1.27	0.84	0.71	0.82

Khaki American B	12.8	0.26	3.2	37.4	84	9.4	7.5	1.25	0.8	0.75	0.78
Dark Brown	12.1	0.24	3	36.9	83	9.1	7.2	1.26	0.78	0.76	0.76
Light Green	10.8	0.21	2.8	34.5	79	8.4	6.8	1.23	0.73	0.8	0.72
Dark Green	11.1	0.22	2.9	35	80	8.7	6.9	1.24	0.74	0.79	0.73
D-Brown (Local)	12.5	0.25	3.1	36.2	82	9	7	1.29	0.77	0.77	0.75
L-Brown (Variant)	12.9	0.27	3.3	37.1	84	9.2	7.4	1.24	0.79	0.75	0.77
Mean	12.9	0.27	3.3	37.6	84.3	9.3	7.5	1.26	0.8	0.74	0.78
LSD (0.05)	0.78	0.03	0.27	1.62	2.8	0.46	0.38	0.04	0.05	0.06	0.04

Photosynthetic rate, stomatal conductance, and chlorophyll content were reduced in all genotypes under water stress, but light brown and khaki genotypes maintained higher values. PEG-based screening further supported their drought resilience through higher STI and MP values.

Multivariate Analysis

PCA separated genotypes based on performance under stress:

Principal components 1 and 2 explained over 72% of total variation.

Traits like fiber strength, boll weight, and chlorophyll content contributed the most to genotypic differentiation under drought. Light brown and khaki American A clustered with white genotypes in the drought-tolerant quadrant, showing potential for breeding drought-resilient colored cotton.

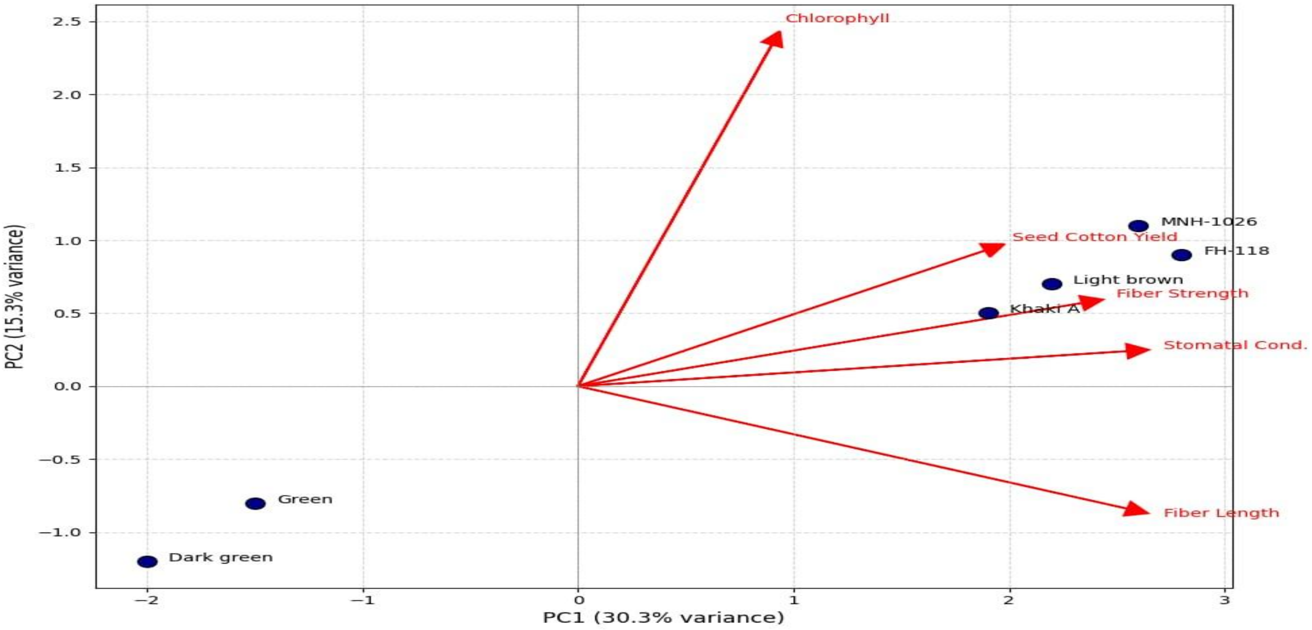

Figure 5. PCA Biplot Showing Genotypic Clustering under Drought Stress.

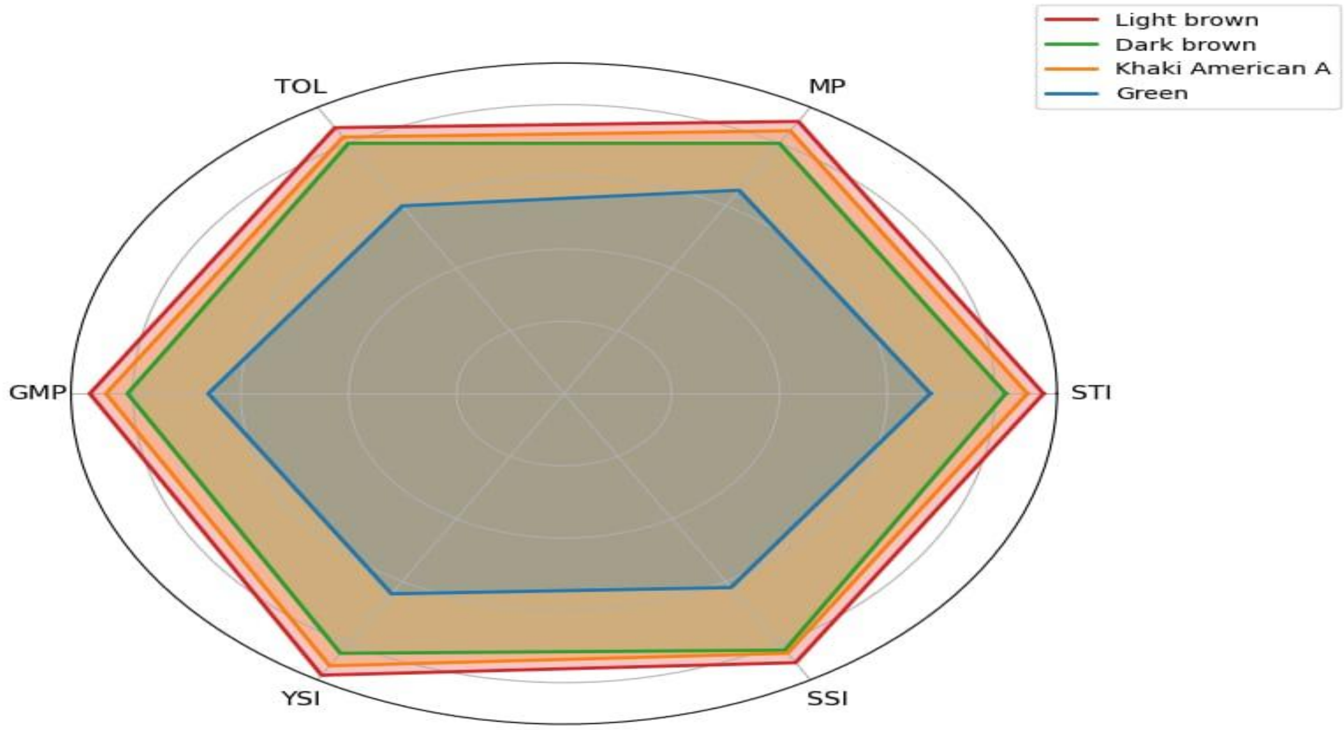

Figure 6. Radar Chart of Drought Tolerance Indices for Colored Genotypes

DISCUSSION

The current study successfully combined genetic variability analysis and drought stress screening to evaluate naturally colored cotton genotypes for yield and fiber quality improvement. Significant genotypic variability was observed for most morphological, yield, and fiber quality traits under normal and stress conditions, indicating the presence of exploitable genetic diversity among the tested lines. These findings align with previous studies emphasizing the genetic potential of colored cotton genotypes for improvement through targeted breeding programs (Dutt et al., 2004; Hua et al., 2007).

Genotypic Potential of Colored Cotton Under Normal Conditions

Under normal irrigation, white cotton genotypes such as FH-118 and MNH-1026 outperformed colored lines in almost all traits, particularly in fiber length and strength. However, the superior performance of light brown and khaki American A genotypes in traits like boll number, seed cotton yield, and fiber strength demonstrates the potential of these lines for future hybridization efforts. Previous literature suggests that while white cotton generally exhibits better fiber quality (Martin & Haigler, 2007), some colored genotypes may harbor favorable alleles for yield-related traits (Rodgers et al., 2008).

The positive correlations found between boll weight, lint weight, and seed cotton yield are consistent with findings by Razzaq et al. (2014) and Ahmed et al. (2020), where these traits were identified as important yield determinants**.** Path coefficient analysis (Table 5) further confirmed that boll number, seed index, and fiber uniformity had the strongest direct effects on yield, validating their utility as selection criteria in colored cotton breeding.

Impact of Drought Stress on Colored Cotton

Drought stress significantly impacted growth, yield, and fiber quality traits across all genotypes, with particularly sharp declines observed in green and dark green colored cotton lines. These results are in line with prior findings that drought negatively affects boll development, photosynthesis, fiber elongation, and micronaire values in cotton (Pettigrew, 2004; Sekmen et al., 2014; Wang et al., 2016).

Among the colored genotypes, light brown and khaki American A demonstrated relatively stable performance under drought stress, maintaining better photosynthetic efficiency, chlorophyll content, and boll retention, as shown in figure 4. This suggests that some colored cotton lines possess inherent physiological mechanisms to tolerate limited water availability, likely through improved root systems, osmotic adjustment, and antioxidant activity (Zhao et al., 2020; Hu et al., 2019).

Physiological screening further highlighted the importance of chlorophyll content, stomatal conductance, and transpiration rate as indicators of drought resilience. These results agree with the findings of Ullah et al. (2017) and Abdelraheem et al. (2020), who reported that maintaining higher photosynthetic activity under stress conditions is associated with better yield stability.

The physiological patterns observed notably the relative maintenance of chlorophyll content and higher photosynthetic rates in Light Brown and Khaki American A under limited irrigation are consistent with adaptive drought mechanisms. Maintenance of chlorophyll indicates reduced photo-oxidative damage and improved pigment stability (Ullah et al., 2017). Higher net photosynthesis under stress may reflect better stomatal regulation and sustained mesophyll capacity, which together helps maintain carbon assimilation and boll filling (Pettigrew, 2004).

Furthermore, genotypes that showed favorable root: shoot ratios in PEG screening likely possess better early root vigor and osmotic adjustment capacity, permitting continued water uptake under soil drying. These traits such as root architecture, osmolyte accumulation and antioxidant enzyme activity have been associated with drought tolerance in cotton and can explain the comparatively stable yields of certain colored genotypes (Hu et al., 2019; Zhao et al., 2020). Integrating such physiological indicators into selection schemes therefore improves the likelihood of identifying genotypes that will perform under field water limitations.

PEG-Based Lab Screening and Drought Indices

The laboratory-based PEG screening provided additional validation of field performance under drought**.** Light brown and dark brown genotypes showed better root-shoot balance, germination rates, and drought tolerance indices (e.g., STI and MP), reinforcing their potential for stress-tolerant breeding. These results support earlier research suggesting that early vigor, germination efficiency, and biomass stability under osmotic stress are reliable indicators of drought adaptation (Gowda et al., 2011; Xiao et al., 2020).

Breeding Implications and Future Directions

The identification of colored genotypes with favorable yield and fiber traits under both normal and stress conditions is a significant step toward developing dual-purpose cotton lines. Light brown and khaki American A**,** when crossed with elite white cultivars such as FH-118**,** may serve as useful parents in breeding programs targeting both eco-friendly pigmentation and stress resilience**.**

Moreover, the use of physiological traits in selection, such as photosynthetic rate, stomatal regulation, and chlorophyll content, should be further emphasized in breeding pipelines for drought-prone environments. Integration of marker-assisted selection or genomics-assisted breeding could accelerate the improvement of colored cotton varieties by targeting quantitative trait loci (QTLs) linked to yield and stress response.

CONCLUSIONS

The present study demonstrates that naturally colored cotton genotypes possess significant genetic variability and differential responses to drought stress, which can be effectively exploited for sustainable cotton improvement. While white cotton genotypes outperformed colored lines in yield and fiber quality under optimal conditions, certain colored genotypes, notably light brown and khaki American A, showed promising performance in both normal and water-limited environments.

Drought stress significantly reduced key agronomic and fiber traits across all genotypes, yet some colored genotypes maintained physiological stability and fiber integrity, indicating the presence of adaptive drought-tolerance mechanisms. The integration of field performance**,** physiological screening, and lab-based PEG assays provided a comprehensive framework to assess drought resilience in cotton.

Correlation and path analyses revealed that boll weight**,** lint weight, and fiber length are reliable predictors of yield, and these traits should be prioritized in selection. Moreover, physiological indicators like chlorophyll conten**t** and photosynthetic rate can be incorporated into breeding programs as early markers for drought tolerance.

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AUTHOR CONTRIBUTIONS

Z.A. and M.N.R. conducted experiments and data analysis; A.F. conceived and supervised the study; S.H. and S.I. contributed to statistical analysis and manuscript editing; A.H., F.Z.A.K., and H.H. provided field and laboratory support. All authors reviewed and approved the manuscript. $^{+}$These authors contributed equally to this work.

COMPETING OF INTEREST

No conflicts of interest have been disclosed by the authors.

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