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DROUGHT TOLERANCE ASSESSMENT IN UPLAND COTTON USING MULTIVARIATE ANALYSIS

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SUMMARY

Reduced crop productivity caused by water deficit conditions due to erratic rainfall and rising temperature is a crucial concern. The presented study aimed at determining the potential yield of 14 upland cotton lines and cultivars (T-1001, T-860, T-1033, T-1037, T-1002, T-1003, T-1005, T-1048, T-1024, T-1050, Guliston, C-6524, T-1023, and T-1068), carried out during the crop season of 2023–2024. The research used a randomized complete block design (RCBD) with three replications under optimal and water deficit conditions. Most drought indices showed significant variations among the cotton genotypes. The ranking method indicated that indices, i.e., mean productivity (MP), geometric mean productivity (GMP), stress tolerance index (STI), mean relative performance (MRP), relative efficiency index (REI), and relative drought index (RDY), proved correlated with seed cotton yield. Cluster analysis and three-dimensional plots identified the cotton lines with the highest drought resistance. Principal component analysis (PCA) explained 84.09% of the variation, with the PC1 suggesting consistent yield potential. The biplot showed MP, GMP, STI, MRP, REI, and YI were the best indices for selecting drought-tolerant lines, viz., T-1005, T-1002, T-1003, and T-1050. These cotton genotypes can be effective as base material in breeding drought-tolerant cotton cultivars.

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Keywords: Upland cotton (*G. hirsutum* L.), multivariate analysis, drought tolerance indices, water deficit conditions, cluster analysis, principal component, correlation, seed cotton yield

Key findings: The optimal irrigation and water stress conditions negatively affected the yield-related traits in upland cotton. The cotton lines T-1005, T-1002, T-1003, T-1024 and T-1050 appeared more stable and performed better for various yield-attributing variables under optimal and water deficit conditions.

INTRODUCTION

Drought stress is a primary environmental and abiotic factor affecting cotton growth, yield, and quality worldwide. Therefore, the identification and development of drought-tolerant genotypes is a priority for sustaining cotton production under water-limited conditions (Nabiev *et al.,* 2020; Shavkiev *et al.,* 2023; Shavkiev *et al.,* 2025). Multivariate analysis has proven to be an effective tool in evaluating the genetic variation, understanding genotype-environment interactions, and identifying the drought-tolerant genotypes based on various indices and traits.

Cotton (*Gossypium* spp.) is a vital crop that provides natural fiber, edible oil, and other byproducts (Samanov *et al*., 2024; Azimov *et al*., 2025; Chorshanbiev *et al*., 2025). Among the four cultivated species, upland cotton (*Gossypium hirsutum* L.) is the most widely grown, accounting for approximately 90% of global cotton production (Amanov *et al*., 2020; Azimov *et al*., 2024a). However, its productivity is highly sensitive to drought, which affects root development, plant height, overall growth, seed cotton yield, and fiber quality traits (Sanaev *et al*., 2021). In drought-prone regions, such as Uzbekistan, water stress has led to a 25%–35% decline in seed cotton yield (Shavkiev *et al*., 2021).

The drought tolerance indices provide an efficient technique to screen the vast germplasm in different crop plants. However, the research on drought tolerance indices regarding screening enormous cotton genotypes is insufficient. The various indices related to drought tolerance provide an extent of tolerance to drought based on the yield losses due to drought stress, with these indices having served to screen various genotypes under drought stress conditions (Azimov *et al.,* 2024b).

Development and selection of drought-resistant genotypes under water deficit conditions is one of the primary tasks in current breeding programs. However, identifying genotypes with drought tolerance is more difficult due to genotype-by-environment interactions and limited knowledge about the stress tolerance mechanisms. Therefore, applying various advanced techniques has continued for the assessment of genetic variation and stability in crop genotypes for drought tolerance (Fernandez, 1992).

The stress-tolerant index (STI) proved to be as effective as, if not more effective than, other drought tolerance indices in selecting favorable corn cultivars under both stress and non-stress conditions (Moghaddam and Hadi-Zadeh, 2002). The findings of Khalili *et al*. (2004) showed that selecting potential cotton hybrids with higher seed cotton is more effective under stress and non-stress environments, based on geometric mean productivity (GMP) and STI indices. Fischer and Maurer (1978) presented a stress susceptibility index (SSI) and reported an association of a lower SSI value with drought resistance in crop genotypes.

Lower stress tolerance index (STI) values indicate a crop genotype's yield may remain comparable under normal conditions while exhibiting resistance to drought stress (Rosielle and Hamblin, 1981). Previous studies have shown these indices are useful for classifying crop genotypes with stable productivity under water-limited conditions (Golabadi *et al*., 2006). The identification and selection of genotypes based on a combination of GMP and SSI indices may serve as a more reliable criterion for improving drought tolerance in common beans (Ramirez and Kelly, 1998).

Table 1. Origin of the upland cotton lines.

Genotypes	Origin	Genotypes	Origin
T-1001	*G. hirsutum* L. x *G. trilobum* L.	T-1023	*G. hirsutum* L. x *G. hirsutum* L.
T-1002	*G. hirsutum* L. x *G. trilobum* L.	T-1033	*G. hirsutum* L. x *G. thurberi* L.
T-1003	*G. hirsutum* L. x *G. trilobum* L.	T-1037	*G. hirsutum* L. x *G. sturtianum* L.
T-1005	*G. hirsutum* L. x *G. trilobum* L.	T-1024	*G. hirsutum* L. x *G. bickii* L.
T-860	*G. hirsutum* L. x *G. hirsutum* L.	T-1068	*G. hirsutum* L. x *G. hirsutum* L.
C-6524	*G. hirsutum* L. x *G. hirsutum* L.	T-1050	*G. hirsutum* L. x *G. thurberi* L. *x G. anomalum* L.
T-1048	*G. hirsutum* L. x *G. hirsutum* L.	Guliston	*G. hirsutum* L. x *G. hirsutum* L.

It is crucial to identify specific selection indices for effectively distinguishing high-yielding cotton lines under drought stress conditions to enhance seed cotton yield and stability under stressful environments. Therefore, this study aimed to evaluate 14 cotton lines (Table 1) and cultivars to identify drought-tolerant genotypes using various drought tolerance indices under both optimal and water deficit conditions.

MATERIALS AND METHODS

Plant material and growing conditions

The study transpired in the crop season of 2023–2024 in Tashkent Region, Uzbekistan (41.389°N, 69.465°E), characterized by cold winters and prolonged hot and dry summers. The region has an annual photoperiod of 16 h of light and eight hours of darkness. The research focused on evaluating the genetic potential and drought tolerance of 14 upland cotton (*G. hirsutum* L.) genotypes originating from Uzbekistan. The genotypes used in the latest study included T-1001, T-1002, T-1003, T-1005, T-860, C-6524, T-1048, T-1023, T-1033, T-1037, T-1024, T-1068, T-1050, and Guliston.

The conduct of the experiment used a randomized complete block design (RCBD) with a factorial arrangement and three replications under both optimal and deficit irrigation conditions. Cotton plants, grown in furrows 20 m long, had a plant spacing of 20 cm and a row spacing of 90 cm. Optimal irrigation maintained soil moisture at 70%–72%, while deficit irrigation maintenance was at 50%–52%, as measured using a moisture tester. The separation of full (optimal) and deficit irrigation treatments occurred from a designated distance. Figure 1 presented details on maximum and minimum temperatures, air humidity, and total rainfall recorded during the study period.

The irrigation schedule followed a 1-2-1 sequence, meaning one application before flowering, two during the flowering phase, and one before boll opening. Specifically, applying 900 m^3/ha of water ensued before flowering, with two applications of 1200 m^3/ha each provided during the flowering phase and 900 m^3/ha given again before the boll-opening stage. Additionally, developing an irrigation technique materialized in response to water scarcity. This method follows a 0-1-0 sequence, in which the application of 1200 m^3/ha of water once took place during flowering (Shavkiev *et al.,* 2022). This adjustment offers a water-efficient solution for cotton cultivation under limited water availability.

Estimation of drought tolerance indices

The 22 drought tolerance indices for various characteristics, when calculated, used the optimal and deficit values. Table 2 shows the formulas for calculating drought tolerance indices. The symbols $\bar{Y}p$, $\bar{Y}s$, Ys, and Yp reflect the seed cotton yield under stress and non-stress circumstances, respectively.

Statistical analysis

The collection of data on all parameters came from nine randomly selected plants in each genotype plot, with the seed cotton yield (g/1.5 m^2) computed for the whole plot. The

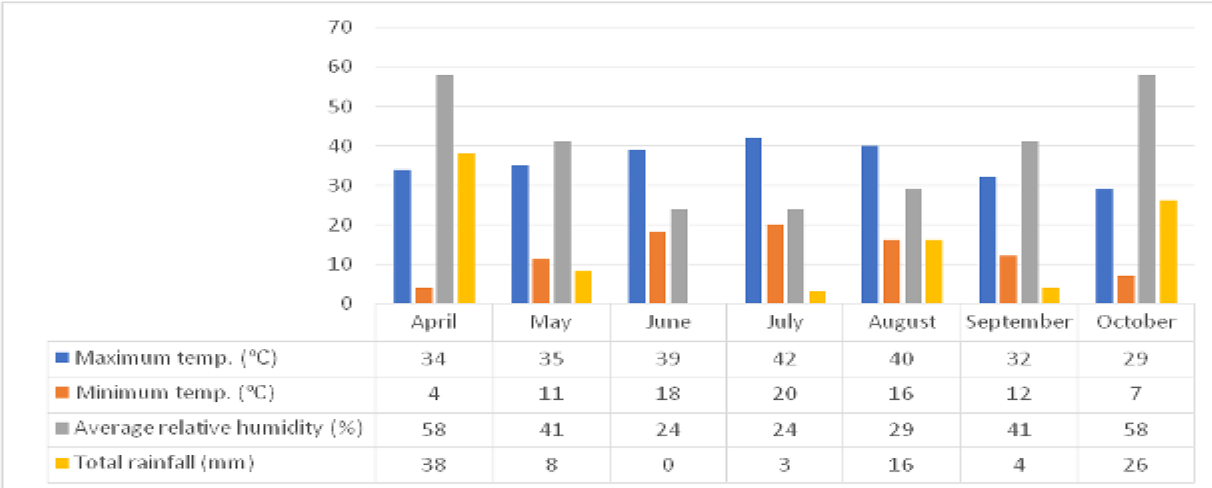

Figure 1. Maximum and minimum temperatures, air humidity, and the total rainfall during the upland cotton study period. *https://pogoda1.ru/tashkent* (Maximum and Minimum temp. [℃], Average relative humidity [%]), *https://en.tutiempo.net/* (Total rainfall [mm]).

Table 2. Drought tolerance indices with their equations in upland cotton.

No.	Indices	Formula	References
1	Yield Index (YI)	Ys/ ȳs	Lin *et al*. (1986)
2	Yield stability index (YSI)	Ys / Yp	Bouslama and Schapaugh (1984)
3	Stress Intensity (SI)	(Yp-Ys)/ ȳp	Fernandez (1992)
4	Stress susceptibility percentage index (SSPI)	[Yp-Ys /2(ȳp)] ×100	Moosavi *et al*. (2008)
5	Stress Susceptibility Index (SSI)	(1-(Ys/Yp))/ (1- (ȳs/ ȳp))	Fischer and Maurer (1978)
6	Stress tolerance index (STI)	(Yp *Ys) / (ȳp) 2	Fernandez (1992)
7	Drought intensity index (DI)	1-(Ys/Yp)	Beebe *et al*. (2013)
8	Tolerance index (TOL)	Yp – Ys	Rosielle and Hamblin (1981)
9	Geometric mean productivity (GMP)	√(Yp × YS)	Fernandez (1992)
10	Relative drought index (RDI)	(Ys/Yp)/ (ȳs / ȳp)	Fischer *et al*. (1998)
11	Mean relative performance (MRP)	(Ysi / ȳs) + (Ypi / ȳp)	Hossain *et al*. (1999)
12	Harmonic Mean (HM)	2 x (Yp x Ys) / (Yp + Ys)	Dadbakhsh *et al*. (2011)
13	Mean productivity (MP)	(Ys+Yp)/2	(Rosielle and Hamblin (1981)
14	Sensitivity drought index (SDI)	(Yp-Ys)/Yp	Farshadfar and Javadinia (2011)
15	Drought tolerance efficiency (DTE)	(Ys / Yp) * 100	Fischer and Wood (1979)
16	Relative decrease in yield (RDY)	100 – ((Ys/ 100) * Yp)	Farshadfar and Elyasi (2012)
17	Abiotic tolerance index (ATI)	((Yp - Ys) / (ȳp / ȳs)) * (√Yp * Ys)	Moosavi *et al*. (2008)
18	Golden mean (GM)	(Yp + Ys) / (Yp - Ys)	Moradi *et al*. (2012)
19	Drought resistance index (DI)	Ys x (Ys / Yp)/ (ȳs)	Lan (1998)
20	Modified stress tolerance index 1 (MSTIk1)	$((Yp)^2 / (\bar{y}p)^2)$ x STI	Farshadfar and Sutka (2002)
21	Modified stress tolerance index 2 (MSTIk2)	$((Ys)^2 / (\bar{y}s)^2)$ x STI	Farshadfar and Sutka (2002)
22	Stress/non-stress Production Index (SNPI)	(3√ (Ypi + Ysi) / (Ypi - Ysi) * 3√Ypi * Ysi * Ysi)	Moosavi *et al*. (2008)

Yp: Average seed yield of the genotype in conditions of optimal water irrigation; Ys: Average seed yield of the genotype in conditions of water deficit; ȳp: Average seed yield of all genotypes in conditions of optimal water irrigation; and ȳs: Average seed yield of all genotypes under water deficit conditions.

data analysis used the analysis of variance (ANOVA) for the randomized complete block design. The means' further comparison and separation employed the multiple range tests with probability values of 0.05, 0.01, and 0.001 (Steel and Torrie, 1984). Determining the association between seed cotton yield per plant with each water regime and drought tolerance index was successful. The cotton lines attained classification based on seed cotton yield (g/plant), submerged regimes, and drought tolerance indices. Principal component analysis (PCA) determined the maximum variance from a data set for each component, reducing numerous variables to a smaller number of components.

Similarly, using biplot analysis helped identify the best indices for the selection of drought-tolerant cotton lines with the highest and most stable seed cotton yield based on PC1 and PC2. Cluster analysis of cotton lines, as presented, depended on drought tolerance indices, seed cotton yield, and its components under non-stress and drought-stress conditions. Cluster analysis of the cotton genotypes on seed cotton yield under the non-stress and water stress conditions for 22 drought indices continued using the average linkage algorithm and Euclidean distance measure. Three-dimensional plots for grouping cotton lines based on Yp, Ys, and drought tolerance indices resulted. Statistical analysis used Statgraphics 19, with the figures drawn using RStudio.

RESULTS

Irrigation regimes' effect on yield traits

The results exhibited significant differences among the cotton lines for yield traits, which authenticated considerable effects of irrigation treatments on the lines (Table 3). Water stress conditions instigated a significant reduction in yield traits compared with optimal conditions. The irrigation regimes generally affected plant growth and seed cotton yield, adversely influencing the seed yield per plant by water deficit conditions. Water stress caused a 38.9% reduction in seed cotton yield, along with varying reductions in other traits. Several studies have highlighted the vital role of multivariate analysis in compiling data related to cotton breeding. The utilization of GMP and STI has proven to be helpful, providing accurate guidance in selecting high-yielding cotton hybrids under drought stress conditions (Khalili *et al*., 2004). Past research also identified drought-tolerant cotton lines using STI and GMP indices, emphasizing their correlation with the seed cotton yield (Shavkiev *et al*., 2022).

Cotton lines' comparison based on tolerance indices

In investigating the suitable drought tolerance indices and using them for screening cotton lines under drought stress conditions,

Table 3. Analysis of variance for seed cotton yield in upland cotton genotypes under optimal and deficit irrigation conditions.

Optimal irrigation conditions					
Source	Sum of squares	d.f.	Mean squares	F-Ratio	P-Value
Between groups	395.899	13	30.4537	12.39	0.0000
Within groups	68.7997	28	2.45713		
Total (Corr.)	464.698	41			
Deficit irrigation conditions					
Source	Sum of squares	d.f	Mean squares	F-Ratio	P-Value
Between groups	1466.42	13	112.802	69.60	0.0000
Within groups	45.3831	28	1.62083		
Total (Corr.)	1511.81	41			

measuring and comparing the seed cotton yield under non-stress (Yp) and drought-stress (Ys) conditions succeeded (Table 4). All drought indices revealed significant differences among the cotton lines.

Based on the SI, SSPI, and SSI, the cotton advance lines T-860, C-6524, T-1037, and T-1023 appeared to be drought-sensitive and had the lowest seed cotton yield under water deficit conditions (Table 4). However, the cotton lines T-1002, T-1003, T-1005, T-1024, and T-1050 displayed the highest values for the drought tolerance indices YI, YSI, STI, and DTE. Based on the seed cotton yield under drought stress conditions, the cotton lines T-1002, T-1003, T-1005, T-1024, and T-1050 resulted in the maximum drought tolerance under drought stress conditions. However, other cotton lines emerged as semi-tolerant and semi-sensitive to drought stress conditions.

Correlation analysis

The correlation coefficient between the investigated indices and seed cotton yield showed all indices as significantly positively and negatively correlated with seed yield under drought stress conditions (Table 5). However, a positive correlation was evident between the seed cotton yield under the non-stress conditions and the abiotic tolerance index (ATI) (0.596*) and modified stress tolerance index 1 (MSTik1) (0.705**). The results further revealed seed cotton yield under non-stress conditions (Yp) as significantly positively correlated with the indices ATI and MSTik1. Seed cotton yield under stressed conditions (Ys) indicated substantial positive correlations with the tolerance indices YI, YSI, STI, MP, GMP, MRP, RDI, DI, DM, DTE, HM, MSTik1, MSTik2, and SNPI.

Principal component analysis

Multivariate analysis, such as principal component analysis (PCA), cluster analysis, and biplot, provided a comprehensive approach for evaluating the cotton genotypes. The PCA aims to earn fewer linear combinations of the variables that are descriptive for most variations in the observed data. The application of PCA results to the variables in the correlation coefficient matrix revealed three principal components with eigenvalues above one, which explained 84.09% variation for drought tolerance indices (Figure 2).

The first component explained about 67.54%, the second explained 15.55%, while the third one described 0.19% of the observed variation. The commonality of each variable, when calculated, took the sum of the squared loadings for that variable. The results also expressed the PC1's positive correlation with almost all the drought indices, except for RDY, SDI, SSI, SNPI, and GM, which occurred negatively (Figure 2). Therefore, the PC1 can be a nominee for a potentially stable yield component. The PC2 had a positive association with the drought indices YPI, RDY, MP, SDI, TOL, ATI, SSPI, SSI, SNPI, and GM. The PC3 displayed positive linkages with the tolerance indices RDY, SDI, TOL, ATI, SSPI, SSI, SNPI, and GM. Thus, the study identified PC2 and PC3 as sensitive to stress components.

Cluster analysis

Cluster analysis indicated, based on stress tolerance indices, the cotton lines divided into three groups, with seven, two, and five genotypes, respectively (Figure 3). The first group had the highest values for MP, MRP, GMP, REI, STI, RDI, DI, GM, DTE, and YI, and tended to be the most desirable cluster under non-stress and drought stress conditions. The tolerant group contains the cotton lines T-1005, T-1002, T-1003, and T-1050. The second group had average indicator values, and the cotton lines in this group were apparently stable under non-stress conditions, finding genotypes as semi-sensitive and semi-tolerant. The third group of genotypes (T-1023, T-1033, and T-1037) emerged to be susceptible to drought stress conditions and were evidently suitable only under irrigated conditions. Three-dimensional plots also confirmed the presented results. The cluster analysis based on the traits under both water regimes clustered the cotton lines into five separate groups (Figure 3).

Table 4. Indicators of water deficit tolerance in the upland cotton genotypes.

Genotypes	YI	YSI	SI	SSPI	SSI	STI	DI	STI	GMP	RDI	MRP	HM	MP	SDI	DTE	RDY	ATI	GM	DI	MSTIk1	MSTIk2	SNPI
T-1001	1.04	0.64	0.36	18.09	0.94	0.65	0.36	19.38	43.26	1.03	2.05	42.21	44.33	0.36	64.12	81.29	520	4.57	0.64	0.66	0.71	259.0557
T-1002	1.22	0.72	0.30	14.98	0.75	0.80	0.28	16.05	47.81	1.15	2.27	47.15	48.47	0.28	71.59	77.15	476	6.04	0.72	0.89	1.18	308.8804
T-1003	1.18	0.70	0.31	15.45	0.78	0.76	0.30	16.55	46.80	1.13	2.22	46.08	47.52	0.30	70.34	78.10	480	5.74	0.70	0.83	1.07	297.9455
T-1005	1.13	0.69	0.31	15.60	0.81	0.71	0.31	16.71	45.24	1.12	2.15	44.49	46.00	0.31	69.26	79.53	469	5.51	0.69	0.73	0.92	282.3044
T-860	0.74	0.43	0.61	30.75	1.51	0.49	0.57	32.94	37.59	0.69	1.81	34.43	41.04	0.57	42.73	85.87	767	2.49	0.43	0.57	0.27	190.1557
C-6524	0.75	0.44	0.59	29.26	1.47	0.49	0.56	31.34	37.31	0.71	1.80	34.40	40.47	0.56	44.18	86.08	725	2.58	0.44	0.53	0.27	189.6792
T-1048	0.99	0.69	0.27	13.73	0.81	0.55	0.31	14.70	39.70	1.12	1.89	39.03	40.37	0.31	69.19	84.24	362	5.49	0.69	0.44	0.54	232.9346
T-1023	0.68	0.44	0.54	26.79	1.47	0.40	0.56	28.70	34.05	0.71	1.64	31.38	36.95	0.56	44.05	88.41	606	2.57	0.44	0.37	0.19	165.7689
T-1033	0.96	0.58	0.44	21.94	1.12	0.62	0.42	23.51	42.05	0.93	2.00	40.50	43.66	0.42	57.58	82.32	613	3.71	0.58	0.66	0.57	241.7382
T-1037	0.76	0.51	0.46	23.21	1.30	0.44	0.49	24.86	35.70	0.81	1.70	33.71	37.80	0.49	50.50	87.26	550	3.04	0.51	0.39	0.26	183.8523
T-1024	1.06	0.73	0.24	12.20	0.71	0.59	0.27	13.06	41.22	1.18	1.96	40.71	41.73	0.27	72.93	83.01	334	6.39	0.73	0.48	0.67	249.6388
T-1068	0.92	0.60	0.38	19.08	1.06	0.54	0.40	20.43	39.31	0.96	1.86	38.05	40.62	0.40	59.80	84.54	498	3.98	0.60	0.49	0.45	221.0906
T-1050	1.21	0.72	0.30	14.78	0.74	0.78	0.28	15.83	47.44	1.16	2.26	46.79	48.09	0.28	71.74	77.50	466	6.08	0.72	0.86	1.15	305.5567
Guliston	1.10	0.69	0.30	15.20	0.81	0.67	0.31	16.29	43.81	1.11	2.08	43.08	44.56	0.31	69.10	80.80	442	5.47	0.69	0.65	0.81	269.1458

Yield Index (YI), Yield Stability Index (YSI), Stress Intensity (SI), Stress Susceptibility Percentage Index (SSPI), Stress Susceptibility Index (SSI), Stress Tolerance Index (STI), Drought Intensity Index (DI), Stress Tolerance Index (STI), Geometric Mean Productivity (GMP), Relative Drought Index (RDI), Mean Relative Performance (MRP), Harmonic Mean (HM), Mean Productivity(MP), Sensitivity Drought Index (SDI), Drought Tolerance Efficiency (DTE), Relative Decrease in Yield (RDY), Abiotic Tolerance Index (ATI), Golden Mean (GM), Drought Resistance Index (DI), Modified Stress Tolerance Index 1 (MSTIk1), Modified Stress Tolerance Index 2 (MSTIk2), and Stress/Non-stress Production Index (SNPI).

Table 5. Correlation coefficient among drought tolerance indices in upland cotton.

Indices	Yp	Ys	YI	YSI	SI	SSPI	SSI	STI	DI	STI	GMP	RDI	MRP	HM	MP	SDI	DTE	RDY	ATI	DM	DI	MSTik1	MSTik2
Yp																							
Ys	0,162																						
YI	0,165	0,999***																					
YSI	-0,159	0,946***	0,945***																				
SI	0,347	-0,868***	-0,866***	-0,980***																			
SSPI	0,336	-0,874***	-0,872***	-0,981***	0,999***																		
SSI	0,164	-0,945***	-0,943***	-0,999***	0,980***	0,982***																	
STI	0,427	0,960***	0,961***	0,819***	-0,697***	-0,706**	-0,816***																
DI	0,159	-0,946***	-0,945***	-1,000***	0,980***	0,981***	0,999***	-0,819***															
STI	0,337	-0,874***	-0,872***	-0,981***	0,999***	1,000***	0,982***	-0,706**	0,981***														
GMP	0,411	0,965***	0,966***	0,831***	-0,711**	-0,719**	-0,828***	0,999***	-0,831***	-0,718**													
RDI	-0,164	0,944***	0,942***	0,999***	-0,980***	-0,981***	-0,999***	0,815***	-0,999***	-0,981***	0,827***												
MRP	0,438	0,957***	0,958***	0,815***	-0,689**	-0,698**	-0,812***	0,998***	-0,815***	-0,698**	0,999***	0,812***											
HM	0,306	0,988***	0,988***	0,887***	-0,785***	-0,792***	-0,885***	0,990***	-0,887***	-0,792***	0,993***	0,884***	0,988***										
MP	0,566*	0,905***	0,906***	0,722**	-0,576*	-0,585*	-0,718**	0,986***	-0,722*	-0,585*	0,984***	0,717**	0,989***	0,957***									
SDI	0,159	-0,946***	-0,945***	-1,000***	0,980***	0,981***	0,999***	-0,819***	1,000***	0,981***	-0,831***	-0,999***	-0,815***	-0,887***	-0,722**								
DTE	-0,161	0,946***	0,944***	0,999***	-0,980***	-0,981***	-1,000***	0,818***	-0,999***	-0,981***	0,830***	0,999***	0,814***	0,886***	0,720**	-0,999							
RDY	-0,423	-0,961***	-0,962***	-0,821***	0,700**	0,709**	0,818***	-0,999***	0,821***	0,709**	-0,998***	-0,817***	-0,998***	-0,990***	-0,985***	0,821	-0,820***						
ATI	0,596*	-0,690**	-0,688***	-0,880***	0,954***	0,952***	0,883***	-0,466	0,880***	0,952***	-0,479	-0,882***	-0,455	-0,574*	-0,320	0,880	-0,881***	0,470					
DM	-0,136	0,936***	0,935***	0,984***	-0,957***	-0,960***	-0,985***	0,814***	-0,984***	-0,960***	0,823***	0,986***	0,813***	0,874***	0,723**	-0,984	0,985***	-0,817***	-0,866***				
DI	-0,159	0,946***	0,945***	1,000***	-0,980***	-0,981***	-0,999***	0,819***	-1,000***	-0,981***	0,831***	0,999***	0,815***	0,887***	0,722**	-1,000	0,999***	-0,821***	-0,880***	0,984***			
MSTik1	0,705**	0,807***	0,809***	0,576*	-0,413	-0,424	-0,571*	0,939***	-0,576*	-0,423	0,930***	0,570***	0,940***	0,884***	0,978***	-0,576	0,574*	-0,938***	-0,143	0,582*	0,576*		
MSTik2	0,325	0,973***	0,974***	0,862***	-0,760**	-0,769**	-0,860***	0,985***	-0,862***	-0,768**	0,982***	0,858***	0,981***	0,984***	0,953***	-0,862	0,861***	-0,987***	-0,561***	0,869***	0,862***	0,896***	
SNPI	0,299	0,989***	0,990***	0,890***	-0,789**	-0,797***	-0,888***	0,990***	-0,890***	-0,796***	0,992***	0,887***	0,988***	0,999***	0,955***	-0,890	0,889***	-0,990***	-0,583***	0,883***	0,890***	0,883***	0,990***

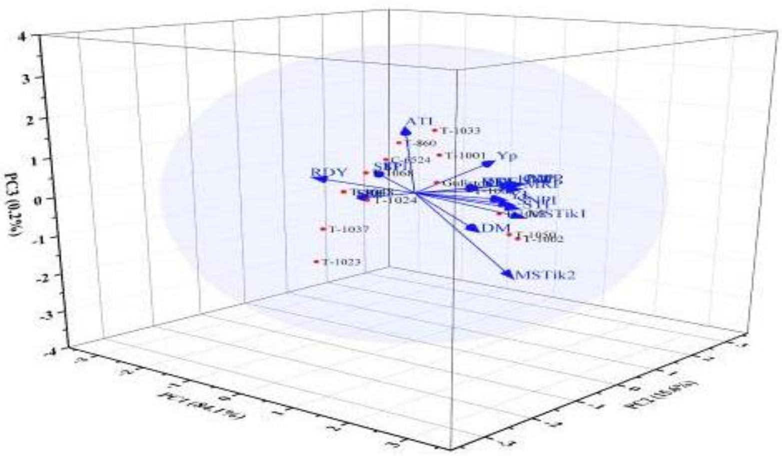

Figure 2. Principal component analysis of the upland cotton genotypes based on drought tolerance indices.

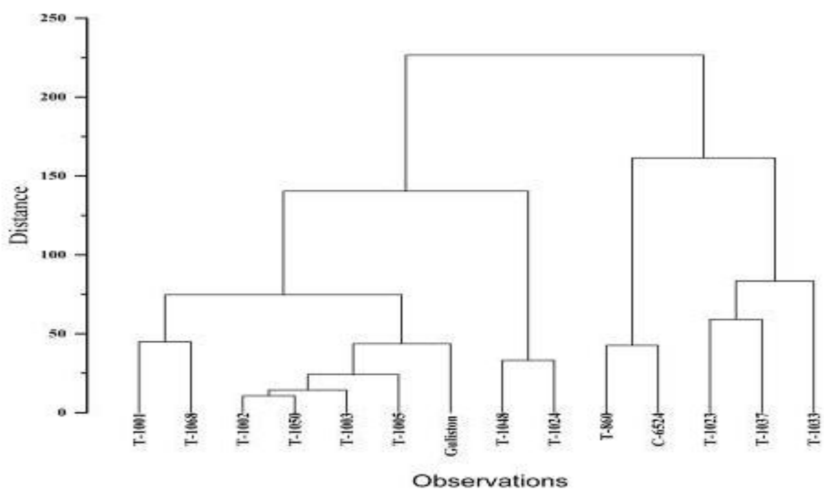

Figure 3. Cluster analysis of the upland cotton genotypes based on drought tolerance indices.

DISCUSSION

Past investigations revealed seed cotton yield and its attributes incurred significant influences from irrigation regimes (Shavkiev *et al.,* 2020; Khamdullaev *et al.,* 2021; Azimov *et al*., 2024c). Previous studies have also reported that drought stress conditions remarkably reduce cotton productivity by decreasing primary yield-related traits, such as the number of bolls per plant and boll weight (Makamov *et al.,* 2023).

For the identification of drought-tolerant lines as per indices, calculating the mean ranking and the standardized deviation of the ranks of drought tolerance criteria also took place. In consideration of all indices, the cotton lines T-1002, T-1003, T-1005, T-1024, and T-1050 exhibited the best average ranking with low standard deviation and, hence, reached distinction as the most drought-tolerant genotypes. The cotton lines T-860, T-1023, and T-1033 proved to be the most sensitive to drought stress conditions. The promising results were also greatly analogous to past findings in wheat (Farshadfar *et al*., 2012) and maize (Khalili *et al*., 2004). Results in the ranking method showed the highest seed cotton yield under the non-stress condition resulted in the cotton genotypes C-6524, T-860, T-1050, T-1002, T-1033, and T-1003. However, the genotypes Guliston, T-1001, T-1002, T-1003, T-1005, T-1024, and T-1050 were promising under drought stress conditions. The cotton genotypes Guliston, T-1001, T-1002, T-1003, T-1005, and T-1050 performed better under non-stress and stressed conditions.

Therefore, various traits could be favorable as important criteria for the prediction of seed cotton yield under drought stress conditions, with the same also confirmed in past studies on maize (Golbashy *et al.*, 2010). A suitable index must have a significant positive correlation with yield under both conditions (Mitra, 2001). For the determination of the most drought-tolerant criteria, the correlation coefficient between Yp, Ys, and other quantitative indices of drought tolerance succeeded calculations (Table 5). Results disclosed the seed cotton yield under non-stress conditions (Yp) as significantly positively correlated with indices TOL, MP, GMP, and REI. However, a noteworthy negative correlation was evident between Y_p and SSPI. Seed cotton yield under stressed conditions (Ys) appeared substantially positively correlated with the indices TOL, MP, GMP, REI, RDI, DI, RDY, DTE, and YI.

A notable negative correlation of Ys manifested with the indices MRP, STI, and SSPI. The results demonstrated that indices have the highest association with the seed cotton yield under non-stress (Yp) and drought-stress (Ys) conditions, which were the most suitable indices to select the drought-tolerant lines. Past research indicated the STI was more efficient in selecting desirable corn genotypes under non-stress and stress conditions (Golbashy *et al.,* 2010). Outcomes further revealed drought tolerance indices MP, GMP, STI, MRP, REI, RDY, DI, and YI as the most suitable indices and can be beneficial as indicators for screening the drought-tolerant cotton lines.

The biplot diagram exhibited that drought indices MP, GMP, STI, HARM, MRP, REI, and YI were the best indices for choosing the drought-tolerant lines with high and stable seed cotton yield under both water regimes. These lines were T-1001, T-1002, T-1003, T-1005, and T-1050 (Figure 1). In the presented study, the efficiency of PCA for adequate separation of genotypes to drought tolerance indices was also confirmatory in different crop species, i.e., wheat (Farshadfar *et al.,* 2012) and rice (Aminpanah *et al.,* 2018). Except for the indices DI, GM, and SNPI under non-stress, and SSI and GM under drought stress conditions, all other indices have shown significant positive correlation with seed cotton yield. It indicates more suitability of these indices for the selection of drought-tolerant genotypes.

Screening for drought-tolerant lines using the ranking method, cluster analysis, three-dimensional plots, and principal component analysis identified the cotton lines T-1002, T-1003, T-1005, and T-1050 as the most drought-tolerant genotypes. Therefore, these genotypes become highly recommendable for use as parental genotypes in the improvement of drought tolerance. Additionally, the results signified that among drought tolerance indices, the MP, GMP, STI, MRP, REI, and YI are the most suitable indicators for screening drought-tolerant cotton genotypes.

CONCLUSIONS

Drought tolerance index indicators attained detection based on the principal component and cluster analyses for drought tolerance. The cotton lines T-1033, T-860, and T-1023 proved to be prone to water deficit conditions. For better seed cotton yield, the cotton lines T-1003, T-1050, T-860, T-1033, and C-6524 could be applicable as suitable donors for selection. The cotton genotypes T-1002, T-1003, T-1005, T-1024, T-1050, and Guliston resulted in being positive donors in the selection for drought tolerance.

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