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PIMA COTTON (*GOSSYPIUM BARBADENSE* L.) LINES ASSESSMENT FOR DROUGHT TOLERANCE IN UZBEKISTAN

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SUMMARY

Globally, increasing water and energy demand is expected to reach 6.9 trillion cubic meters by 2030, exceeding 40% of the available water supplies. Climate change and rising temperatures caused water shortages due to lesser and irregular rainfalls, leading to lower production of crops. The research to assess drought tolerance of Pima cotton (*Gossypium barbadense*. L) lines in Uzbekistan revealed the line, T-450 as the most promising for drought environments. The research, in a randomized complete block design (RCBD) in three replications with a factorial arrangement and two irrigation regimes (non-stress and water stress at the seedling stage), was conducted at the experimental field of the Institute of Genetics and Plant Experimental Biology, District Zangi-Ota, Tashkent Region, Uzbekistan. Nine Pima cotton lines, i.e., Сурхон-14 (control cultivar), T-1, T-5440, T-2006, T-10, T-167, T-5445, T-450, and T-663 with diverse agronomic characters, were selected for their potential yield during 2019, 2020, and 2021 cropping seasons under two different environments (optimal and water deficit condition). Drought indices revealed significant differences among lines, except the golden mean (GM). Results in the ranking method indicate that among the drought tolerance indices, mean productivity (MP), geometric mean productivity (GMP), stress tolerance index (STI), mean relative performance (MRP), relative efficiency index (REI), and relative drought index (RDY), show the most suitable indicators because of their high correlation with seed cotton yield. Cluster analysis and three-dimensional plots showed the cotton inbred lines with the highest tolerance to drought under both irrigation conditions. The first three principal components (PCs) explained 67.54% of total variation and the PC1 can be nominated as a potentially stable yield. The biplot diagram based on PCs and drought tolerance indices showed that MP, GMP, STI, MRP, REI, and YI were the best indices for screening the tolerant cotton inbred lines, such as, T-450.

Keywords: Pima cotton lines, non-stress and water stress, cluster analysis, principal component and biplot analyses, correlation, seed cotton yield

Key findings: The optimal irrigation and water stress conditions negatively affected the related traits of seed cotton yield. The line T-450 was found to be more stable and performed better for various yield attributing variables than other genotypes under optimal and water deficit conditions.

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INTRODUCTION

Gossypium species have morpho-biological variations, ranging from annual crops to trees. All the commercially cultivated cotton cultivars come from two species (*G. hirsutum* L. and *G. barbadense* L.) *G. hirsutum* L. is the most cultivated species as it contributes 90% of the world's total cotton production (Khan *et al*., 2007; Khan, 2011; Batool and Khan, 2012; Soomro *et al*., 2012; Hu *et al.,* 2019; Amanov *et al.,* 2020). Currently, the world's cotton area is around 35 million ha, of which about 1.0 million are in Uzbekistan where the cotton is grown under different climatic conditions (Worldbank.org, 2020). In 2020 in Uzbekistan, the total cotton fiber production reached 2800 bales (609.6 metric tons) (Cotton - World Market and Trade, 2022).

Drought highly impacts crop productivity, root development and its system, leaf area, and plant height (Sajid *et al*., 2022). In Uzbekistan, a 25%–35% decrease in cotton production was observed because of high temperature and water stress compared with the previous year (Shavkiev *et al.,* 2019). Water deficit conditions also have an enormous negative impact on seed cotton production. Water stress affects the plant physiology's cellular and molecular mechanisms (Chaves *et al.,* 2003). The demand for water-resistant genotypes is increasing as water resources decline over time. Cotton has a higher tolerance to abiotic stresses than other major crops. However, extreme environmental conditions, like drought, affect the growth, productivity, and even fiber quality of the cotton (Parida *et al.,* 2008).

In plants, the drought tolerance mechanisms have four categories, i.e., drought avoidance, drought tolerance, drought recovery, and drought escape (Fang and Xiong, 2015). The seedling stage already shows tolerance variability, where knowing how a plant responds and behaves during the development of drought-tolerant genotypes is vital. A study reported that the use of different morphological traits can classify the drought sensitivity and tolerance in upland cotton (Jaleel *et al.,* 2009). Significant differences had been reported in various morphological traits, such as, shoot and root length, plant height, bolls per plant, and boll weight (Mahmood *et al.,* 2006). However, root morphology plays a vital role in determining drought response (Basal and Ünay, 2006; Liu *et al.,* 2008). Leaf water content is also a crucial factor in determining drought tolerance, and usually, plants with high water content are drought tolerant plants (de-Brito *et al.,* 2011). The stress susceptibility index (SSI) can be used for screening the genotypes against different abiotic stresses (Fischer and Maurer, 1978). When the SSI is lesser than a unit value indicates that a variety is a drought-tolerant one, but when a value is more than a unit, it indicates that a variety is drought-sensitive (Guttieri *et al.,* 2001). The stress tolerance index (STI) is also very useful in recognizing varieties with a high yield potential under drought and controlled conditions (Fernandez, 1992).

Breeding for drought tolerance is complicated at the lack of fast, reproducible screening techniques, and the inability to create defined drought stress conditions, where large populations can be evaluated efficiently (Ramirez and Kelly, 1998). The drought tolerance indices provide an efficient technique to screen vast germplasm in crop plants. The research work on drought tolerance indices related to screening enormous genotypes in the cotton crop is limited. The various indices related to drought tolerance provide an extent of tolerance to drought based on the yield loss against drought stress, where these indices have been used to screen many genotypes under drought stress conditions (Mitra, 2001).

A study to classify genotypes against drought tolerance suggested various indices based on yield under both normal and drought conditions (Huang and Gao, 2000). Stress tolerance (TOL) shows the yield difference under normal and stress conditions, and mean productivity (MP) refers to an average yield under normal (Yp) and stress (Ys) conditions (Clarke and McCaig, 1982). Fischer and Maurer (1978) introduced the stress susceptibility index (SSI) for screening massive crop germplasm, stating the lower SSI value is associated with drought resistance in crop genotypes. Guttieri *et al.* (2001) found that when the SSI value is less than unity (<1), the genotype is drought tolerant, while if more than unity (>1), the genotype is sensitive to drought. The stress tolerance index (STI) introduced by Fernandez (1992) can be useful to identify high-yielding genotypes under stress and non-stress conditions.

In breeding programs, selecting the best genotypes under drought stress conditions is one of the main goals (Richards *et al.,* 2002). The study of extensive physiological, morphological, and molecular traits can also help improve the drought and salinity tolerance of crops, and most of them are potentially applicable to cotton crop (Ashraf and Ahmad., 2000; Dağdelen *et al.,* 2006; Massacci *et al.,* 2008; Hafeez *et al.,* 2015). Identifying genotypes for drought tolerance is more difficult due to the interactions between the genotypes and the environmental conditions and not having enough knowledge about stress tolerance mechanisms. Therefore, various techniques have been used to assess the genetic variations in crop genotypes for drought tolerance (Fernandez, 1992).

For water stress tolerance, genotype identification at the yielding stage for higher production is vital in crop breeding (Menezes *et al.,* 2014). Fernandez (1992) classified plants according to their performance under stress and non-stress environments into four groups, i.e., genotypes with good performance in both environments (Group A), genotypes with good performance only in non-stress environments (Group B), genotypes with good performance under stress environments (Group C), and genotypes with weak performance under both environments (Group D). Using various drought indices determined drought-tolerant genotypes based on mathematical relation and yield loss between stress and non-stress (optimum) conditions (Rosielle and Hambelen, 1981; Clarke *et al.,* 1992; Fernandez, 1992; Mardeh *et al.,* 2006). Moghaddam and Hadi-Zadeh (2002) found that the STI was more useful in selecting favorable corn cultivars under stressful and stress-free conditions. Khalili *et al.* (2004) showed that based on geometric mean productivity (GMP) and STI indices, cotton hybrids with high yields in both stress and non-stress environments could be selected.

Lower STI values demonstrated that the crop genotype's yield might be at par with each other under normal conditions and/or resistant to drought stress conditions (Rosielle and Hamblin, 1981). Various previous investigations revealed the advantage of these indices for classifying the genotypes with more stable productivity under water-limited conditions (Golabadi *et al.,* 2006). Selection based on combining the GMP and SSI indices may provide a more desirable criterion for improving drought resistance in common beans (Ramirez and Kelly, 1998). To improve cotton yield and its stability in stress environments, identifying specific selection indices is necessary, which can distinguish the high-yielding Pima cotton lines in drought stress conditions. The study's objectives aimed to evaluate several drought tolerance indices and to identify the drought tolerance in nine lines of the Pima cotton.

MATERIAL AND METHODS

Plant material and growing conditions

The study conducted the experiments in 2019, 2020, and 2021 in the Tashkent Region of Uzbekistan (41.389°N and 69.465°E). This region experiences cold winters and long, hot, dry summers. The annual photoperiod (light/dark) is 16/8 h. The study involved the genetic potential and genetic aspects of nine Pima cotton (*Gossypium barbadense* L.) cultivars belonging to Uzbekistan, i.e., Surkhan-14, T-1, T-5440, T-2006, T-10, T-167, T-5445, T-450, and T-663, under optimal and deficit irrigation conditions. These parental cultivars have an average fiber production of 1.0–1.2 tons/hm^2 with varying levels of drought tolerance. The Pima cotton cultivars were grown in a randomized complete block design (RCBD) with a factorial arrangement and three replications under optimal and deficit irrigation conditions. The cotton genotypes were planted with plant and row spacing of 20 and 90 cm, respectively, in 30 m long furrows. Soil moisture content was 66%–70% under optimal irrigation conditions and 49%–55% under deficit irrigation conditions, as calculated with a moisture tester. A specified distance separated the full (optimal) and deficit irrigation conditions.

Temperature increases in April during the cotton sowing season and decreases in late September before the harvest period. Table 1 shows the information on maximum and minimum temperatures, air humidity, and the amount of total rainfall during the study period. Sunny days were between 180–185 days. Rainfall varied from zero to 45 mm during the dry season for five to six months. The crop requires intensive irrigation throughout the vegetative period. Cotton is irrigated by following a 1–2–1 (pre-flowering-flowering-boll opening) sequence with 900 m^3/hm^2 of water applied before flowering, two applications of 1200 m^3/hm^2 each during flowering, and 900 m^3/hm^2 before the boll-opening phases (Xamidov and Matyakubov, 2019). This sequence is an optimal irrigation protocol widely used in cotton production in Uzbekistan. Soil moisture also contributes to water during seed germination. A developed irrigation protocol for water deficit conditions followed a 1–1–0 sequence with 900 m^3/hm^2 of water applied before flowering and one application of 1200 m^3/hm^2 of water each during flowering (Xamidov and Matyakubov,

Table 1. Maximum and minimum temperatures, air humidity, and the amount of total rainfall during the study period.

Months	Maximum temp. (°C)			Minimum temp. (°C)			Average relative humidity (%)			Total rainfall (mm)		
	2019	2020	2021	2019	2020	2021	2018	2020	2021	2019	2020	2021
April	+28°	+27°	+29°	+5°	+4°	+4°	34%	32%	34%	42.38	3.98	4.38
May	+36°	+33°	+35°	+10°	+8°	+10°	26%	30%	33%	11.25	2.95	3.36
June	+36°	+37°	+38°	+16°	+15°	+16°	19%	25%	30%	6.90	1.15	1.90
July	+42°	+43°	+40°	+20°	+20°	+19°	15%	15%	19%	2.43	0.00	0.12
August	+40°	+39°	+36°	+17°	+17°	+15°	14%	14%	18%	0.08	0.00	0.05
September	+36°	+32°	+30°	+10°	+11°	+10°	15%	22%	21%	1.05	0.36	0.31
October	+28°	+29°	+26°	+6°	+3°	+4°	29%	29%	26%	2.78	2.74	2.55

Table 2. Drought tolerance indices with their equations.

Index		Abbr.	Formula	References
1	Mean productivity	MP	(Ypi+Ysi)/2	Rosielle and Hamblin (1981)
2	Mean relative performance	MRP	(Ysi/Ys) + (Ypi/Yp)	Hossain *et al*. (1999)
3	Stress susceptibility index	SSI	1-(Ysi/Ypi))/SI = 1-(Ys/Yp)	Fischer and Maurer (1978)
4	Tolerance index	TOL	Ypi–Ysi	Rosielle and Hamblin (1981)
5	Geometric mean productivity	GMP	√ (Ypi*Ysi)	Fernandez (1992)
6	Relative efficiency index	REI	(Ysi/Ys) *(Ypi/Yp)	Hossain *et al*. (1999)
7	Stress tolerance index	STI	(Ysi*Ypi)/(Yp) ^{2}	Fernandez (1992)
8	Yield index	YI	Ysi/Ys	Gavuzzi *et al*. (1997), Lin *et al*. (1986)
9	Sensitivity drought index	SDI	(Ypi-Ysi)/Ypi	Farshadfar and Javadinia (2011)
10	Relative drought index	RDI	(Ysi/Ypi)/(Ys/Yp)	Fischer and Wood (1979)
11	Drought resistance index	DI	Ysi*(Ysi/Ypi)/(Ys)	Lan (1998)
12	Golden mean	GM	(Ypi+Ysi)/ (Ypi -Ysi)	Moradi *et al*. (2012)
13	Stress susceptibility percentage index	SSPI	((Ypi-Ysi)/(2*Yp)) *100	Moosavi *et al*. (2008)
14	Relative decrease in yield	RDY	100 – ((Ysi/100) *Ypi)	Farshadfar and Elyasi (2012)
15	Drought tolerance efficiency	DTE	(Ysi/Ypi) *100	Fischer and Wood (1981)

Ypi: Average productivity of the genotype in conditions of optimal water irrigation, Ysi: Average plant productivity of the genotype in conditions of water deficit, Yp: Average productivity of all genotypes in conditions of optimal water irrigation, Ys: Average productivity of all genotypes under water deficit conditions.

2019). For crop protection purposes, the insecticides, Bi-58 (BASF, Germany) and Hexachloran were applied for the control of sucking (aphids) and chewing (bollworm) insects, respectively. The seasonal application of fertilizers was performed during tillage and before irrigation per annum with 250:180:115 NPK kg/hm^2.

Estimation of drought tolerance indices

The study calculated all the traits for the 15 drought tolerance indices using the corresponding optimal and water deficit conditions. Table 2 provides the formulas for calculating drought tolerance indices. The symbols of Ysi, Ypi, Ys, and Yp represent the seed cotton yield of each inbred line under stress and non-stress conditions, and inbred line yield means under stress and non-stress conditions, respectively.

Statistical analysis

The study recorded data on all the parameters for nine competitive plants in each genotype plot, and calculated seed cotton yield (g/1.5 m^2) for the entire plot. Data were statistically analyzed using appropriate ANOVA for RCBD. A comparison of means by using multiple range tests at the probability levels of 0.05, 0.01, and 0.001 was calculated (Steel and Torrie, 1984). The correlation of seed yield cotton per plant with each water regime and drought tolerance indices was determined. The classification of lines using seed cotton yield (g/plant) under water regimes and drought tolerance indices was performed. Principal component analysis (PCA) was used to extract the maximum variance from the data set with each component, thus reducing a large number of variables into a smaller number of components.

Biplot analysis was also used to identify the best indices in selecting drought tolerant inbred lines with the highest and most stable seed cotton yield based on PC1 and PC2. Cluster analysis of cotton lines is calculated based on drought tolerance indices, seed cotton yield, and its components in non-stress and drought stress conditions. Cluster analysis of the cotton genotypes, based on seed cotton yield in the non-stress and water stress conditions and nine drought indices, was carried out using the average linkage algorithm and Euclidean distance measure. Three-dimensional plots for grouping cotton lines based on Ypi, Ysi, and drought tolerance indices were drafted. Statistical analysis used Minitab Ver.18 and Excel software. Figures were drawn using Statgraphs 18.

RESULTS AND DISCUSSION

Influence of irrigation regime on yield traits

Table 3 presents the analysis of variance of studied traits on nine cotton inbred lines under non-stress and drought conditions. Results showed significant differences among the cotton inbred lines for yield traits, which authenticated that lines were considerably influenced by irrigation treatments and water stress, leading to a reduction in yield traits compared with optimal conditions (Tables 3 and 4). The irrigation regimes affect the plant growth and seed cotton yield, and in these studies, the seed yield plant^{-1} was adversely affected by the water deficit conditions. The water stress caused a -33.1% reduction in seed cotton yield, and varying reductions for other traits.

Past investigations revealed that irrigation regimes significantly influenced seed cotton yield and its attributes (Bolek, 2007; Shahzad *et al.*, 2016; Zhang *et al.*, 2017). Further researchers reported that drought stress conditions decreased the total productivity of cotton due to a reduction in bolls per plant and the boll weight (Saleem *et al.,* 2015; Wang *et al.,* 2016; Tohir *et al.,* 2018; Shavkiev *et al.,* 2020; Shavkiev *et al.,* 2021). Inbred lines are categorized into four groups based on their performance under non-stress and drought stress environments. These categories are inbred lines expressing uniform superiority in both non-stress and drought conditions (Group A), inbred lines performing favorably only under non-stress conditions (Group B), inbred lines producing relatively higher yield only in stress conditions (Group C), and inbred lines performing poorly in both non-stress and drought stress conditions (Group D). The ideal selection criterion should distinguish Group A from the other three groups of cotton lines.

Comparing inbred lines based on tolerance indices

The study measured the cotton seed yield under both non-stress (Ypi) and drought stress (Ysi) conditions to investigate suitable drought tolerance indices for screening cotton inbred lines under drought conditions (Table 4). All the drought indices revealed significant differences among inbred lines except GM. Based on the STI, MP, GMP, YI, SSPI, and Ypi, the inbred line T-450 showed drought tolerant with the highest STI and cotton seed yield under non-stressed condition (Tables 5 and 6). However, the inbred lines T-10 and T-167 displayed the lowest values for these indices. Other inbred lines showed semi-tolerance and semi-sensitive to drought stress. Moreover, according to seed cotton yield in drought stress conditions (Y_{si}) and YI indices, the inbred lines Surkhan-14, T-5440, and T-5445 were selected as the most relatively tolerant, whereas inbred line T-450 was found the least tolerant under drought stress conditions.

Calculating the mean ranking and the standardized deviation of the ranks of drought tolerance criteria identified the most desirable and drought-tolerant inbred lines per indices. Considering all the indices, cotton’s inbred lines Surkhan-14, T-5440, T-5445, and T-450 exhibited the best mean ranking and almost low standard deviation. Hence, these were identified as the most drought-tolerant genotypes, while lines T-10 and T-167 revealed the most sensitive to drought stress conditions (Tables 5 and 6). Verifying these results were past findings in wheat (Farshadfar *et al*., 2012) and maize (Khalili *et al.,* 2004). Data in the ranking method showed that the highest yields under the non-stress condition were from cotton lines Surkhan-14, T-1, T-2006, T-450, and T-663c, while genotypes Surkhan-14, T-5440, T-5445, and T-450 were promising under drought stress conditions. However, Pima cotton lines Surkhan-14, T-5440, T-5445, and T-450 performed better under non-stress and drought-stress conditions.

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

Source of variation	Degree of freedom (d.f.)	Sum of squares	Mean sum squares	F. calculated values
Optimal irrigation conditions				
Replications	(r - 1) = 2	560.0	280.0	6.1
Genotypes	(t - 1) = 8	721.7	90.2	1.9
Error	(r - 1) × (t - 1) = 16	731.2	45.7	
Total	(r × t) - 1 = 28	2012.9		
Deficit irrigation conditions				
Replications	(r - 1) = 2	2443.6	1221.8	46.2
Genotypes	(t - 1) = 8	676.9	84.6	3.2
Error	(r - 1) × (t - 1) = 16	422.9	26.4	
Total	(r × t) - 1 = 28	3543.6		

Table 4. Seed cotton yield plant^{-1} in Pima cotton lines under optimal and deficit irrigation conditions.

No.	Treatment		2019	2020	2021	Means
1	Surkhan-14	Ypi	76.60	49.67	58.93	61.73
		Ysi	55.57	32.29	38.31	42.06
2	T-1	Ypi	66.3	64.54	57.74	62.86
		Ysi	53.47	32.53	29.10	38.37
3	T-5440	Ypi	60.79	50.46	68.66	59.97
		Ysi	54.90	29.39	39.99	41.43
4	T-2006	Ypi	72.16	69.35	63.75	68.42
		Ysi	45.84	34.25	31.48	37.19
5	T-10	Ypi	58.87	57.61	44.28	53.59
		Ysi	37.60	33.75	25.94	32.43
6	T-167	Ypi	57.78	44.75	48.32	50.28
		Ysi	52.60	25.51	27.55	35.22
7	T-5445	Ypi	55.00	56.03	53.59	54.87
		Ysi	52.18	35.73	34.17	40.69
8	T-450	Ypi	74.99	52.76	55.56	61.10
		Ysi	74.12	38.77	40.83	51.24
9	T-663	Ypi	68.80	61.59	51.28	60.56
		Ysi	51.69	31.92	31.25	38.29

Table 5. Indicators of water deficit tolerance in cotton genotypes.

Cultivars	Ypi	Ysi	MP	MRP	SSI	TOL	GMP	REI	STI	SDI	RDI	DI	GM	SSPI	RDY	DTE	YI
Surkhan-14	61.73	42.06	51.89	2.10	0.32	19.68	50.95	1.10	0.74	0.32	1.02	0.72	5.27	16.60	74.04	68.13	1.06
T-1	62.86	38.37	50.61	2.03	0.39	24.49	49.11	1.03	0.69	0.39	0.91	0.59	4.13	20.66	75.88	61.04	0.97
T-5440	59.97	41.43	50.70	2.06	0.31	18.54	49.84	1.06	0.71	0.31	1.03	0.72	5.47	15.64	75.16	69.08	1.04
T-2006	68.42	37.19	52.81	2.09	0.46	31.23	50.44	1.08	0.72	0.46	0.81	0.51	3.38	26.35	74.55	54.36	0.94
T-10	53.59	32.43	43.01	1.72	0.39	21.16	41.69	0.74	0.49	0.39	0.90	0.49	4.07	17.85	82.62	60.52	0.82
T-167	50.28	35.22	42.75	1.74	0.30	15.06	42.08	0.75	0.50	0.30	1.05	0.62	5.68	12.71	82.29	70.04	0.89
T-5445	54.87	40.69	47.78	1.95	0.26	14.18	47.26	0.95	0.64	0.26	1.11	0.76	6.74	11.96	77.67	74.16	1.03
T-450	61.10	51.24	56.17	2.32	0.16	9.86	55.95	1.33	0.89	0.16	1.25	1.08	11.39	8.32	68.69	83.86	1.29
T-663	60.56	38.29	49.42	1.99	0.37	22.27	48.15	0.99	0.66	0.37	0.94	0.61	4.44	18.79	76.82	63.22	0.97

Mean Productivity (MP), Mean Relative Performance (MRP), Stress Susceptibility Index (SSI), Tolerance Index (TOL), Geometric Mean Productivity (GMP), Relative Efficiency Index (REI), Stress Tolerance Index (STI), Sensitivity Drought Index (SDI), Relative Drought Index (RDI), Drought Resistance Index (DI), Golden Mean (GM), Stress Susceptibility Percentage Index (SSPI), Relative Decrease in Yield (RDY), Drought Tolerance Efficiency (DTE), Yield Index (YI), Yield Stability Index (YSI).

Table 6. Analysis of indices for water deficit tolerance in cotton genotypes (95.0% confidence intervals).

Indices	Means	Standard error	Lower limit	Upper limit	Sigma
Yp	59.26	1.83	55.04	63.48	5.48
Ys	39.66	1.77	35.57	43.74	5.31
MP	2.0	0.062	1.86	2.14	0.18
MRP	0.33	0.03	0.26	0.39	0.09
SSI	19.61	2.09	14.78	24.43	6.27
TOL	48.38	1.47	44.98	51.78	4.42
GMP	1.003	0.06	0.86	1.142	0.18
REI	0.67	0.04	0.58	0.76	0.12
STI	0.33	0.03	0.26	0.39	0.09
SDI	1.00	0.04	0.90	1.10	0.13
RDI	0.66	0.06	0.54	0.81	0.18
DI	5.62	0.79	3.78	7.46	2.39
GM	16.54	1.76	12.47	20.61	5.29
SSPI	76.41	1.42	73.14	79.69	4.26
RDY	67.16	2.89	60.49	73.82	8.67
DTE	1.001	0.04	0.90	1.103	0.13
YI	0.671	0.03	0.60	0.74	0.09

Correlation analysis

The correlation coefficient between the studied traits and seed cotton yield showed that all traits positively correlate with seed yield under both normal and drought stress conditions (Table 7). However, the highest observed correlation was between Ys and drought tolerance efficiency (DTE) (0.99). Therefore, the said trait could be a vital criterion for the prediction of seed cotton yield under drought stress conditions, and past findings in corn also confirmed this (Shoa-Hoseini *et al.*, 2007; Golbashy *et al.*, 2010). A suitable index must have a significant correlation with yield under both conditions (Mitra, 2001). Calculating the correlation coefficient between Yp, Ys, and other quantitative indices of drought tolerance determined the most desirable and drought-tolerant criterion (Table 7). Results showed that yield in non-stress conditions (Yp) significantly and positively correlates with TOL, MP, GMP, and REI. An observation between Y_p with SSPI showed a significant and negative correlation. Seed cotton yield under stressed conditions (Ys) significantly and positively correlates with TOL, MP, GMP, REI, RDI, DI, RDY, DTE, and YI.

A significant negative correlation of Ys was observed with MRP, STI, and SSPI. These results showed that indices that have the highest correlation with yield under non-stress (Yp) and drought stress (Ys) conditions were the most suitable index to select drought-tolerant inbred lines. Mehrabi *et al*. (2011) suggested corn hybrids with high yield may be obtained based on GMP and STI indices. Most of the past research indicated that the STI was more useful to select desirable corn genotypes under non-stress and stress conditions (Moghaddam and Hadizadeh, 2002; Khalili *et al*., 2004; Shoa-Hoseini *et al*., 2007; Golbashy *et al*., 2010). Results further revealed that drought tolerance indices, MP, GMP, STI, MRP, REI, RDY, DI, and YI were found most suitable and can be used as indicators for screening drought tolerant cotton inbred lines.

Principal component analysis

The principal component analysis (PCA) aims to earn a small number of linear combinations of the variables, which are descriptive for most of the variation in the data. PCA results applied to the variables in the correlation coefficient matrix revealed that three principal components with Eigenvalue above 1 explained 96.34% variation for drought tolerance indices (Table 8). The first component explained about 67.54%, the second explained 32.00%, and the third explained 0.393% of the observed variation. The commonality of each variable was calculated by taking the sum of the squared loadings for that variable. The results also showed that PC1 positively correlated with almost all the drought indices, except RDY, SDI, SSI, SNPI, and GM, which were negative. Therefore, the study nominates PC1 as a potential stable yield component. The PC2 positively relates with drought indices Ypi, RDY, MP, SDI, TOL, ATI, SSPI, SSI, SNPI, and GM. The PC3 positively correlated with RDY, SDI, TOL, ATI, SSPI, SSI, SNPI, and GM. Thus, the study results nominate PC2 and PC3 as sensitive to stress components.

The biplot diagram exhibited that drought indices MP, GMP, STI, MRP, REI, and YI, were the best indices in selecting the inbred line T-450 as a drought-tolerant genotype, with stable high seed yield under both conditions (Figure 1). The study presents the efficiency of PCA for adequate separation of inbred lines to drought tolerance indices, which was also confirmed in different species, i.e., maize (Khodarahmpour and Hamidi, 2011), sunflower (Ghaffari *et al*., 2012), wheat (Farshadfar *et al*., 2012), grass pea (Basaran *et al*., 2012), and rice (Rahimi *et al.,* 2013, Marcelo *et al.,* 2017, Aminpanah *et al.,* 2018). Except for DI, GM, SNPI under non-stress and SSI and GM under drought stress conditions, other indices have shown the highest correlation with seed cotton yield indicating more suitability of these indices for selection of resistant cotton inbred lines. Screening the drought-tolerant inbred lines, using the ranking method, cluster analysis, three-dimensional plots, and PCA, separated inbred line T-450 as the most promising drought-tolerant genotype. Therefore, the study recommends the said genotype as the best parental genotype for improving drought tolerance in Pima cotton. In addition, results also showed that, among drought tolerance indices, the MP, GMP, STI, MRP, REI, and YI are the most suitable indicators for screening drought-tolerant Pima cotton inbred lines.

Cluster analysis

Cluster analysis showed the cotton inbred lines based on indices applied to the three groups, including one, two, and six inbred lines (Figure 2). The first group had the highest MP, MRP, GMP, REI, STI, RDI, DI, GM, DTE, and YI and was considered the most desirable cluster under non-stress and drought stress conditions (Tolerant group that contains inbred line T-

Table 7. Correlation coefficient among drought tolerance indices.

Indices	Yp	Ys	MP	MRP	SSI	TOL	GMP	REI	STI	SDI	RDI	DI	GM	SSPI	RDY	DTE
Yp																
Ys	0.32															
MP	0.73*	0.88**														
MRP	0.35	-0.77*	-0.38													
SSI	0.60	-0.56	-0.11	0.96***												
TOL	0.73*	0.88**	0.99***	-0.38	-0.11											
GMP	0.72*	0.89**	0.99***	-0.40	-0.13	0.99***										
REI	0.71*	0.90**	0.99***	-0.41	-0.14	0.99***	0.99***									
STI	0.35	-0.77*	-0.38	1.00***	0.96***	-0.38	-0.40	-0.41								
SDI	-0.34	0.77*	0.38	-0.99***	-0.95***	0.38	0.41	0.41	-0.99***							
RDI	0.02	0.95***	0.69*	-0.93**	-0.79*	0.69*	0.71*	0.72*	-0.93***	0.93***						
DI	-0.14	0.85**	0.55	-0.94***	-0.84**	0.54	0.57	0.57	-0.94***	0.94***	0.96***					
GM	0.60	-0.56	-0.11	0.96***	1.00***	-0.11	-0.13	-0.14	0.96***	-0.95***	-0.78*	-0.84**				
SSPI	-0.71*	-0.89**	-0.99***	0.41	0.14	-0.99***	-0.99***	-0.99***	0.41	-0.41	-0.72*	-0.57	0.14			
RDY	-0.34	0.78*	0.39	-0.99***	-0.95***	0.39	0.41	0.42	-0.99***	0.99***	0.93***	0.94***	-0.95***	-0.41		
DTE	0.33	0.99***	0.88***	-0.77*	-0.56	0.88***	0.89**	0.90**	-0.77*	0.77*	0.95***	0.86**	-0.56	-0.89**	0.77*	
YI	-0.35	0.77*	0.38	-1.00***	-0.96***	0.38	0.40	0.41	-1.00***	0.99***	0.92***	0.94***	-0.95***	-0.41	0.99***	0.77*

Table 8. Principal component analysis.

Components	F1	F2	F3	F4	F5	F6	F7	F8
Eigenvalue	11.482	5.441	0.067	0.009	0.001	0.000	0.000	0.000
Variability (%)	67.544	32.004	0.393	0.052	0.004	0.001	0.001	0.001
Cumulative %	67.544	99.548	99.941	99.993	99.997	99.998	99.999	100.000

450). The second group had mean indicator values, and the inbred lines in this group were considered stable in non-stress conditions (semi-sensitive/semi-tolerant). The third group was susceptible to drought stress conditions and only suitable for irrigated conditions (T-10 and T-167). The three-dimensional plots confirm these results. Figure 2 also showed cluster analysis, based on the traits in both environments, and the cotton inbred lines clustered into four separate groups.

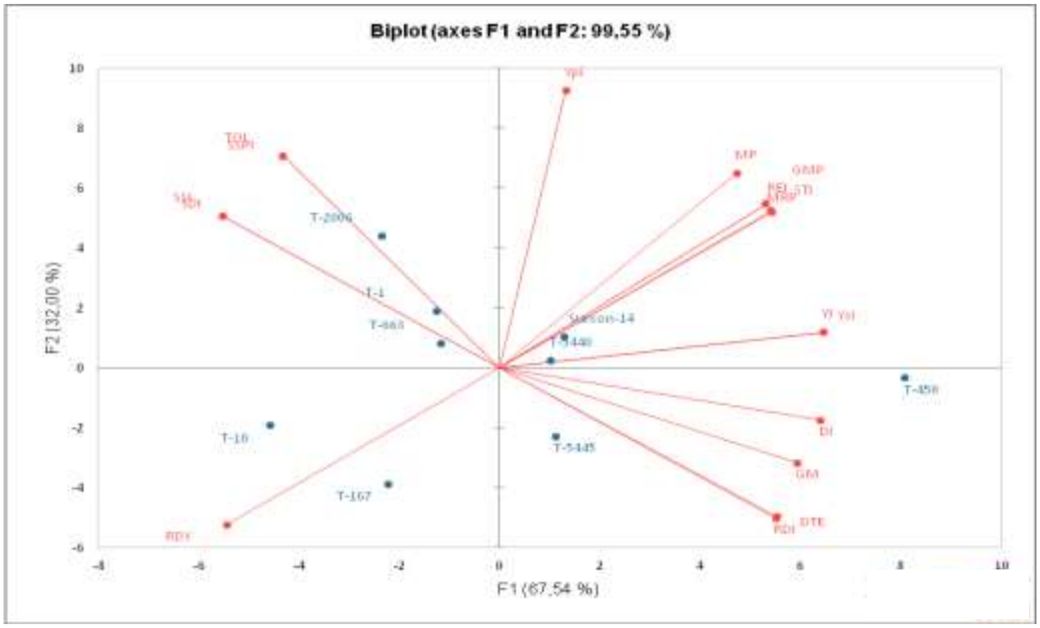

Figure 1. Principal component analysis.

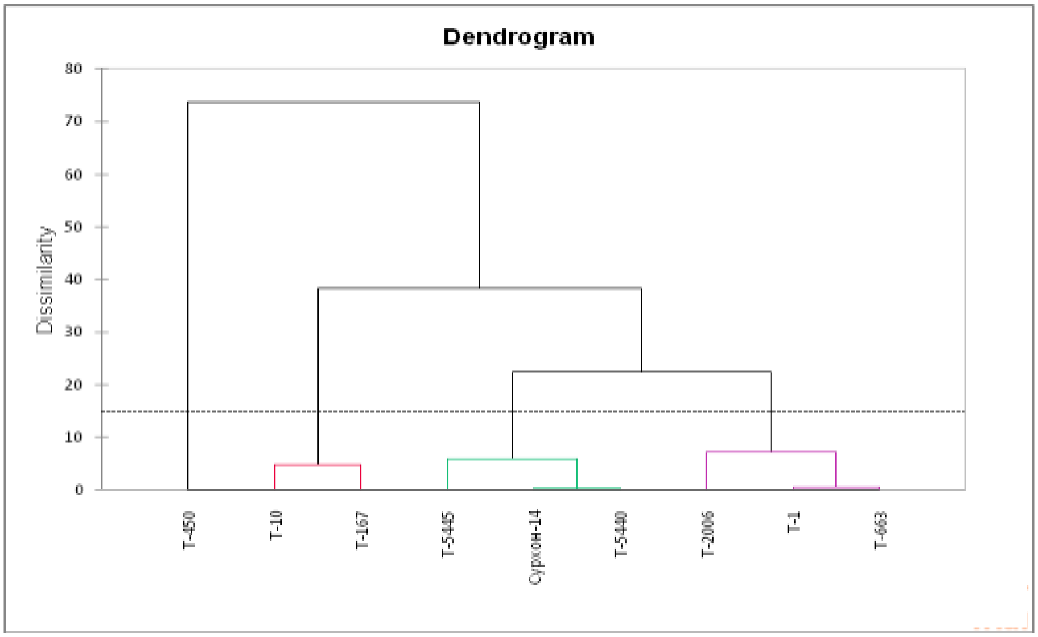

Figure 2. Cluster analysis.

CONCLUSIONS

Drought tolerance index indicators were determined based on the principal component and cluster analysis for water deficit tolerance. The cotton inbred lines T-10 and T-167 were found to be prone to water deficit conditions. In terms of seed cotton yield, inbred lines T-663, T-2006, and Surkhan-14 could be used as suitable donors for selection. The inbred line T-450 was found to be a positive donor in the selection for drought.

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