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RESEARCH ARTICLE

Assessment of agro-morphological traits and yield-based tolerance indices in sesame (*Sesamum indicum* L.) genotypes under drought stress

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Abstract

Sesame (*Sesamum indicum* L.) is one of the most important oilseed crops of the world, particularly tropical areas. Its production is significantly affected by drought stress. The present study was performed to assess the efficiency of existing criteria for the selection of tolerant cultivars while evaluating sesame genotypes under drought conditions. Various agro-morphological traits along with some drought tolerance indices were used to evaluate 15 sesame genotypes under drought conditions. A moderate to high heritability was estimated for plant height (0.55), no. of capsules (0.72), capsule diameter (0.60), no. of seeds per capsule (0.43) and seed yield (0.53). On average, the seed yield of genotypes was reduced by 45% under water stress. Seed yield was significantly positively correlated with the no. of capsules, capsule diameter, and no. of seeds per capsule under both normal and drought conditions. The number of capsules and capsule diameter were suggested as potential criteria for indirect yield selection under drought stress. Chinese (G01), Naz Chand Shakhe (G05), and Darab1 (G04) genotypes were identified as the most tolerant based on the average ranking of indices. Stress/non-stress production index (SNPI), yield index (YI), and drought resistance index (DI) were suggested as the most efficient drought tolerance indices according to principal component analysis and correlations. The evaluation criteria proposed in this study can be used for efficient selection of drought-tolerant genotypes in sesame. Moreover, reported tolerant and sensitive genotypes can be used in future studies and breeding programs in sesame under drought stress.

Keywords: Agro-morphological traits, drought stress, tolerance indices, evaluation, Sesamum

Introduction

Drought is one of most important environmental stresses limiting growth and production of crop plants especially in dry climate zones. Sesame (*Sesamum indicum* L.) is one of the important oil seed crops with numerous industrial, medicinal, and nutritional applications (Morris 2002). Its seeds contain significant amounts of protein, oil, and natural antioxidants including sesamin, sesamolin, and tocopherols (Bedigian 2010). Sesame is usually grown in arid and semi-arid regions of the world. Limited water resources, inappropriate distribution of annual rainfall throughout the seasons and inadequate management of existing resources along with high temperature at the sesame growing season in dry areas lead to frequent drought stress (Islam et al. 2016). Sesame is almost adapted to drought and can survive in these conditions (Zhang et al. 2019). However, the seed yield of sesame is significantly reduced under drought stress, especially at flowering stage (Golestani and Pakniyat 2015; Islam et al. 2016; Dossa et al. 2019). Severe drought has been reported to considerably diminish seed quality and yield of sesame by reducing the number of capsules and

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the number of seeds per capsule (Golestani and Pakniyat 2015; Saljooghianpour and Javadzadeh 2018; Kouighat et al. 2021). Since the most critical issue in crop production is a good and stable yield under stress conditions (Bhargava and Sawant 2013). Therefore, improving drought tolerance is one of the main goals of sesame breeding programs to ensure sufficient yield under stress conditions.

From the agricultural points of view, drought tolerance is defined as crop ability to maintains its yield under water deficit (Tardieu et al. 2018). Drought tolerance is a complex quantitative trait affected by several genetic and physiological factors (Kebede et al. 2019; Shah et al. 2020). Screening and selection of available germplasm are the simplest yet one of the most efficient strategies for improving the complex traits (Gupta et al. 2004). Numerous criteria including morphological, physiological, and biochemical traits have been proposed to evaluate the genotypes under different environmental stresses and to determine their tolerance or sensitivity (Kebede et al. 2019; Shah et al. 2020). Seed yield is one of the most common criterion traits for improving plant tolerance under adverse environmental conditions such as drought stress (Bennani et al. 2016; Rauf et al. 2016). Evaluation and selection of genotypes based on seed yield are usually done either by direct or indirect approaches. Direct selection based on yield was reported inefficient under drought stress due to the great impact of the environment on it and a low heritability (Badu-Apraku and Fakorede 2013; Rauf et al. 2016). Several researchers suggested the evaluation of germplasm based on yield components traits to improve the efficiency of selection (Kuol 2004; Roy and Basu 2009; Boussakouran et al. 2019).

However, it has been shown that secondary traits often did not have higher heritability than seed yield or had a low correlation with it (Bernier et al. 2008; Roy and Basu 2009). Thus, evaluation based on yield is still one of the main options available for selection under water stress. Several drought tolerance indices such as mean productivity (MP), geometric mean productivity (GMP), harmonic mean (HM), yield stability index (YSI), stress susceptibility index (SSI), tolerant index (TOL), yield index (YI), stress/non-stress production index (SNPI), drought resistance index (DI), and stress tolerant index (STI) were proposed to offer the best genotypes based on yield under both normal and drought conditions (Rosielle and Hamblin 1981; Bouslama and Schapaugh Jr 1984; Fischer and Maurer 1987; Fernandez 1992; Gavuzzi et al. 1997; Schneider et al. 1997; Jusheng 1998; Farshadfar and Sutka 2002; Moosavi et al. 2008). Many studies on different plants used drought indices to evaluate and identify tolerant cultivars (Boureima et al. 2016; Mau et al. 2019; Mickky et al. 2019). However, there are various opinions on the most efficient indices for selection under drought stress. Mau et al. (2019) suggested STI, GMP, MP, HM, YI, and SNPI indices as the most effective indices in selecting drought tolerant cultivars. Abebe et al. (2020) found YSI as a useful index to identify stable genotypes under different water conditions.

Due to the importance of the mentioned strategies, the current study was aimed to find out the most appropriate morphological traits related to yield for evaluation and selection of genotypes under drought stress. Also, another goal of this study was to evaluate the efficiency and accuracy of drought tolerance indices as selection criteria. Moreover, it was targeted to identify and introduce the most tolerant genotype with high yield in both normal and drought conditions to use in breeding programs.

Materials and methods

Plant materials, experimental design and growth conditions

The seeds of sesame genotypes including common varieties and landraces were collected all over Iran and were cataloged in the plant breeding department of Sari University of Agricultural Sciences and Natural Resources, Iran. Based on the germination and vigor tests and initial field experiments fifteen genotypes were selected to use in this study (Table 1). The seeds were sown in the field during the normal growing seasons (9 May, 2019) based on split-plot in a randomized complete block design with three replicates and two factors including water treatments (control and drought-stressed) as main-plots and genotypes as sub-plots. Each block consisted of three 2 m-long lines with a 50 cm row spacing between the lines and 15cm plant spacing within the lines. Two meter interval was considered between control and drought plots to prevent water leakage into dry blocks during the stress application. Fertilizers

Table 1. General details of studied sesame genotypes.

No.	Accession No.	Name	Type	Origin
G01	SaSiG010	China1	Variety	China
G02	SaSiG004	Moghan17	Variety	Iran
G03	SaSiG001	Naz Tak	Variety	Iran
G04	SaSiG006	Darab1	Variety	Iran
G05	SaSiG002	Naz Chand	Variety	Iran
G06	SaSiG011	Dashtestan2	Variety	Iran
G07	SaSiG003	Oltan	Variety	Iran
G08	SaSiG012	Halil	Variety	Iran
G09	SaSiG007	Yellow-White	Variety	Pakistan
G10	SaSiG016	Kerman	Landrace	Iran
G11	SaSiG019	Amiri	Landrace	Iran
G12	SaSiG020	Kazemi	Landrace	Iran
G13	SaSiG009	American	Variety	U.S.
G14	SaSiG008	Sudan	Variety	Sudan
G15	SaSiG021	Gachsaran	Landrace	Iran

including 150 Kg N/ha, 50 Kg P/ha, 50 Kg K/ha were applied equally in all blocks before planting based on soil analysis. An additional 50 Kg N/ha also was applied at the beginning of flowering. The weeds were controlled manually twice during the experiment. The drip irrigation system was used to irrigate the field. All plants were well-watered (based on field capacity) until the flowering stage. Half of the plants were drought-stressed by withholding the irrigation for 24 days (3.5 weeks) between flowering and maturing stage (2 July, 2019). The half of the plant population was irrigated normally as control. After the drought treatment period, the plants were watered normally, and their soil moisture was kept at an optimum condition until the harvesting stage (6 October, 2019).

Morphological traits and drought tolerance indices

At the harvesting stage, agro-morphological traits including plant height (cm), number of capsules, stem diameter (cm), capsule diameter (cm), seeds per capsule, 100-seed weight (g), and seed yield (g/plant) were measured for each block (average of 5 individual plants). Based on the seed yield under drought stress and normal conditions various drought tolerant indices including SSI, GMP, MP, HM, TOL, STI, YI, YSI, DI, and SNPI were calculated using their respective formulas (Table 2). Genotypes were ranked ordinary based on average yield under normal and drought conditions along with each index value and its favorable interpretation.

Statistical analysis

All statistical analyses of this study were performed using XLSTAT (Addinsoft, France), a Microsoft Excel (Microsoft, USA) add-on. The morphological data were subjected to the Analysis of Variance (ANOVA) and Fisher's Least Significant Difference (LSD) to determine the significance of the differences ($p < 0.05$). The broad sense heritability (H^2) of traits was calculated using the expected value of

Table 2. Description of the drought tolerance indices used in this study.

Index	Formula	Reference
Stress Susceptibility Index (SSI)	$SSI = \frac{1 - \frac{Y_D}{Y_N}}{1 - \frac{\bar{Y}_D}{\bar{Y}_N}}$	(Fischer and Maurer 1987)
Geometric Mean Productivity (GMP)	$GMP = \sqrt{Y_D \times Y_N}$	(Schneideret al. 1997)
Mean Productivity (MP)	$MP = \frac{Y_D + Y_N}{2}$	(Rosielle and Hamblin 1981)
Harmonic Mean (HM)	$HM = \frac{2(Y_N \times Y_D)}{Y_N + Y_D}$	(Farshadfar and Sutka 2002)
Tolerant Index (TOL)	$TOL = Y_N - Y_D$	(Rosielle and Hamblin 1981)
Stress Tolerant Index (STI)	$STI = \frac{Y_D \times Y_N}{(\bar{Y}_N)^2}$	(Fernandez 1992)
Yield Index (YI)	$YI = \frac{Y_D}{\bar{Y}_D}$	(Gavuzzi et al. 1997)
Yield Stability Index (YSI)	$YSI = \frac{Y_D}{Y_N}$	(Bouslama and Schapaugh Jr 1984)
Drought Resistance Index (DI)	$DI = \frac{Y_D \times \frac{Y_D}{Y_N}}{\bar{Y}_D}$	(Jusheng 1998)
Stress Non-Stress Production Index (SNPI)	$SNPI = \sqrt[3]{\frac{Y_N + Y_D}{Y_N - Y_D}} \times \sqrt[3]{Y_N \times Y_D^2}$	(Moosavi et al. 2008)

Y_N = Average yield per plant of each genotype under normal condition; Y_D = Average yield of per plant of each genotype under drought condition; $\bar{Y}_N$ = Average yield per plant of all genotype under normal condition; $\bar{Y}_D$ = Average yield per plant of all genotype under drought condition.

Table 3. Mean squares of the analysis of variance and estimates of broad-sense heritability for morphological traits of sesame genotypes under normal and drought conditions

Source of Variation	df	Mean Square						
		Plant height (cm)	No. of capsules	Stem diameter (cm)	Capsule diameter (cm)	Seeds per capsule	100-Seeds weight (g)	Yield per plant (g)
Block	2	42.94	0.60	0.21	0.26	0.21	0.00041	2.51
Condition (C)	1	6046.13**	10361.25**	2.42*	12.08*	154.27**	0.00753*	440.47**
Error (a)	2	18.82	4.67	0.08	0.23	1.32	0.00010	0.04
Genotype (G)	14	649.34**	385.50**	1.06**	4.61**	8.03**	0.00090**	15.93**
C × G	14	149.52**	26.76**	0.10	0.88**	2.22**	0.00084**	3.28**
Error (b)	56	27.92	10.91	0.09	0.19	0.80	0.00013	1.21
δ^2_g		83.30	59.79	0.16	0.62	0.97	0.00001	2.11
δ^2_i		40.53	5.28	0.00	0.23	0.48	0.00024	0.69
δ^2_p		151.76	75.99	0.26	1.04	2.24	0.00038	4.00
H^2		0.55	0.79	0.62	0.60	0.43	0.02581	0.53

*, ** Significant differences at $P < 0.05$ and $P < 0.01$, respectively

δ^2_g = Genetic variance; δ^2_i = Genotype–environment interaction variance; δ^2_p = Phenotypic variance; H^2 = Broad-sense heritability

Table 4. The correlation coefficient among morphological traits of sesame genotypes under normal and drought conditions

Traits	No. of capsules	Stem diameter	Capsule diameter	Seeds per capsule	100-seed weight	Yield per plant
Plant height						
Normal	-0.155	-0.119	-0.207	0.138	0.366*	0.089
Drought	0.324*	-0.133	0.264	0.171	0.310*	0.454**
No. of capsules						
Normal		0.007	0.478**	0.202	-0.163	0.812**
Drought		0.110	0.378*	0.056	0.015	0.780**
Stem diameter						
Normal			0.151	-0.236	0.000	0.028
Drought			0.250	-0.078	0.207	0.213
Capsule diameter						
Normal				-0.133	-0.001	0.543**
Drought				-0.258	0.078	0.480**
Seeds per capsule						
Normal					0.327*	0.357*
Drought					0.429**	0.354*
100-weed weight						
Normal						0.295*
Drought						0.283

*, ** Significant differences at $P < 0.05$ and $P < 0.01$, respectively

variance as described by Nyquist and Baker (1991). The correlation among traits in each condition, and between yields and drought tolerance indices estimated using Pearson's correlation coefficient. The principal component analysis (PCA) followed by varimax rotation with the Kaiser normalization (Kaiser 1958) was applied to yields and drought tolerance indices data. The results of PCA after varimax rotation were visualized using a biplot. The cluster analysis was performed on yields and drought tolerance indices data by using the Euclidean distance coefficient and WPGMA (weighted pair group method with arithmetic mean) clustering method.

Results and discussion

ANOVA, heritability, and means comparisons of morphological traits

The results of ANOVA (Table 3) showed a highly significant difference (p < 0.01) among genotypes for all studied traits under different water conditions. A highly significant difference (p<0.01) between drought and normal conditions was observed for plant height, number of capsules, number of seeds per capsule, and yield per plant. The stem diameter, capsule diameter, and 100-seed weight also were significantly different (p<0.05) under drought stress compared to normal conditions. The interactions between water conditions and genotypes (C×G) were highly significant in all studied traits except stem diameter. Moderate to high heritability was estimated for all the traits, except for 100-seed weight which showed low heritability (0.026). The number of capsules had the highest heritability (0.79) among the studied traits. Similar to our results, a moderate to high heritability was reported for yield components in previous studies on sesame (Monpara and Khairnar 2016; Dossa et al. 2019). Yield components with high heritability have a better response to selection and are easier to improve (Rauf et al. 2016). Therefore, such traits including the number of capsules and capsule diameter could be used as effective criteria for indirect selection under drought stress.

The average morphological traits of sesame genotypes in normal and drought conditions were compared to measure the effect of drought stress (Supplementary Table S1(. Drought stress resulted in a strong negative effect on the number of capsules and yield per plant with a reduction of 45.62 and 45.73% compared normal conditions, respectively. The stem diameter and 100-seed weight had lowest decrease among studied traits with 7.66 and 6.40% reduction under drought conditions, respectively. The highest yield per plant was found in G02, G05, G11, and G01genotypes with an average of 12.47, 12.43, 11.64, and 11.44 g in normal condition, respectively. However, G05, G01, G04, and G11genotypes with 6.88, 6.85, 6.81, and 6.56 g had the highest yield per plant under drought stress, respectively. Previous studies on sesame under drought stress revealed a significant reduction in yield per plant and other agro-morphological traits, in line with our results (Kim et al. 2006; Ozkan and Kulak 2013; Saljooghianpour and Javadzadeh 2018). Overall, significant variations for yield and other morphological traits were observed among sesame genotype under both drought and normal conditions. Variation in yield-related traits is one of the necessities of selection to improve drought tolerance of genotypes (Kuol 2004). Previous studies on sesame have similarly reported significant variation for yield components among their studied genotypes under drought stress (Kuol 2004; Boureima et al. 2016).

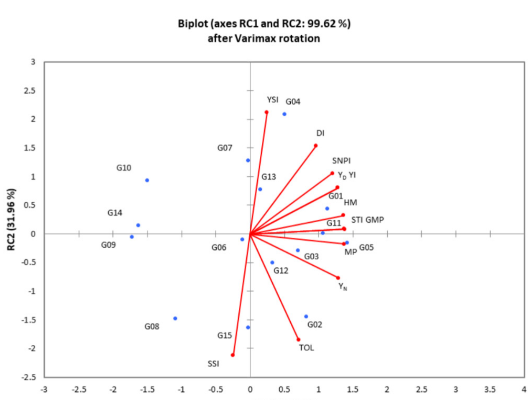

Fig. 1. Bi-plot of PCA followed by varimax rotation on estimated drought tolerance indices among sesame genotypes. RC= Rotated component; YN= Average yield/ plant under normal condition; YD = Average yield/ plant under drought condition; SSI= Stress Susceptibility Index; GMP = Geometric Mean Productivity; MP= Mean Productivity; HM= Harmonic Mean; TOL= Tolerant Index; STI= Stress Tolerant Index; YI= Yield Index; YSI= Yield Stability Index; DI= Drought Resistance Index and SNPI= Stress Non-Stress Production Index.

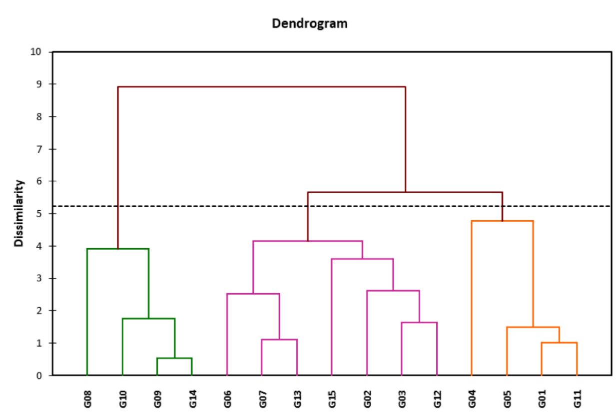

Fig. 2. Dendrogram of cluster analysis on estimated drought tolerance indices among sesame genotypes. The clusters were truncated based on the entropy threshold

Table 5. The correlation coefficients among Y_N, Y_D, and drought tolerance indices

Variable	Y_D	SSI	GMP	MP	HM	TOL	STI	YI	YSI	DI	SNPI
Y_N	0.73**	0.18	0.92**	0.96**	0.87**	0.79**	0.91**	0.73**	-0.18	0.40	0.64*
D_Y		-0.53*	0.94**	0.89**	0.97**	0.16	0.94**	1.00**	0.53*	0.91**	0.99**
SSI			-0.22	-0.10	-0.32	0.74**	-0.22	-0.53*	-1.00**	-0.82**	-0.63*
GMP				0.99**	0.99**	0.48	1.00**	0.94**	0.22	0.72**	0.89**
MP					0.97**	0.58*	0.99**	0.89**	0.10	0.64*	0.83**
HM						0.38	0.99**	0.97**	0.32	0.79**	0.93**
TOL							0.47	0.16	-0.74**	-0.25	0.03
STI								0.94**	0.22	0.72**	0.88**
YI									0.53*	0.91**	0.99**
YSI										0.82**	0.63*
DI											0.96**

*, ** Significant differences at $P < 0.05$ and $P < 0.01$, respectively.
Y_N = Average yield per plant under normal condition; Y_D= Average yield per plant under drought condition; SSI = Stress Susceptibility Index; GM = Geometric Mean Productivity; MP = Mean Productivity; HM = Harmonic Mean; TOL = Tolerant Index; STI = Stress Tolerant Index; YI = Yield Index; YSI = Yield Stability Index; DI = Drought Resistance Index and SNPI = Stress Non-Stress Production Index

Correlation analysis

To evaluate the relationships between the morphological trait of sesame under both drought and normal conditions, the correlation analysis was performed, and results were compared together (Table 4). Under normal water conditions, the yield of per plant was significantly correlated with the number of capsules, capsule diameter, number of seeds per capsule ($P<0.01$), and 100-seed weight ($p<0.05$). The 100-seed weight was also significantly correlated with plant height and number of seeds per capsule ($p<0.05$). A significant correlation was observed between capsule diameter and the number of capsules ($p<0.01$). Consistent with our results, Monpara and Khairnar (2016) showed that seed yield had a highly significant positive correlation with the number of capsules per plant under normal water conditions. On the other hand, yield per plant was significantly correlated with plant height, the number of capsules, capsule diameter ($p<0.01$), and number of seeds per capsule ($p<0.05$) under drought stress. The 100-seed weight was significantly correlated with the number of seeds per capsule ($p<0.01$) and the plant height ($p<0.05$). The number of capsules was also significantly correlated with the plant height and capsule diameter ($p<0.05$). Similarly, significant positive correlations of seed yield with plant height, the number of capsules, and the number of seeds per capsule were reported by Saljooghianpour and Javadzadeh (2018). Secondary traits that show a high positive correlation with seed yield are preferred for selection under drought stress (Roy and Basu 2009). Therefore, the number of capsules and capsule diameter were suggested as potential criteria for indirect selection under drought stress.

Drought-tolerance indices

Genotypes were ordinary ranked by average yields under both water conditions and drought-tolerance indices (Supplementary Table S2). As shown earlier, G02, G05, and G11 genotypes had the highest rank in terms of yield per plant under normal conditions (Y_N), while G05, G01, and G04 genotypes exhibited the highest rank under drought stress (Y_D), respectively. G05 genotype was ranked first in GMP, MP, HM, STI, and YI indices. The first rank in SSI, YSI, DI, and SNPI indices belonged to G04 genotype. However, different indices had different estimates of genotypes, and each suggested different genotypes as drought-tolerant. Therefore, the average rank of each genotype was estimated for a comprehensive conclusion. Accordingly, G01, G05, andG04 genotypes were identified as the most drought-tolerant ones, and G08, G09, and G14 genotypes as the most drought-sensitive ones. Similarly, the average rank of the indices was used to evaluate tolerant genotypes in sesame, rice and mustard (Boureima et al. 2016; Mau et al. 2019; Chugh et al. 2022).

Correlation among drought tolerance indices

Pearson correlation coefficients among drought tolerance indices and yield under both water conditions (Y_N and Y_D) are presented in Table 5. The results showed that there was a significant positive correlation between Y_N and Y_D ($p<0.01$). Previous studies have similarly reported a significant positive correlation between yield under drought and normal conditions (Mau et al. 2019). This suggests that high-yield genotypes under non-stress conditions also might show high yields under drought stress (Abd El-Mohsen et al. 2015). Yet conversely, in the results of the present study, some genotypes (such as G02, G04, and G15) just showed highest yield in one of the environments. Therefore, selection based both on Y_N and Y_D is recommended (Mitra 2001; Nouri et al. 2011) to be used in sesame breeding. Drought tolerance

Table 6. Loadings and squared cosines between drought tolerance indices and rotated components (RC)

Variables	RC1		RC2	
	Loadings	Squared cosines	Loadings	Squared cosines
Y_N	**0.934**	**0.872**	-0.356	0.127
Y_D	**0.928**	**0.861**	0.372	0.139
SSI	-0.179	0.032	**-0.981**	**0.963**
GMP	**0.999**	**0.998**	0.039	0.001
MP	**0.997**	**0.993**	-0.081	0.007
HM	**0.988**	**0.976**	0.150	0.022
TOL	0.514	0.264	**-0.854**	**0.730**
STI	**0.994**	**0.989**	0.040	0.002
YI	**0.928**	**0.861**	0.372	0.139
YSI	0.179	0.032	**0.981**	**0.963**
DI	0.698	0.488	**0.711**	**0.505**
SNPI	**0.869**	**0.755**	0.488	0.238
Variability (%)	67.66		31.96	
Cumulative %	67.66		99.62	

The variables were related to the rotated component (RC), which has a higher squared cosine (bold values)

indices including GMP, MP, HM, STI, YI, and SNPI showed a positive significant correlation with both Y_N and Y_D at $p<0.01$ or $p<0.05$. The TOL also showed a highly significant positive correlation with Y_N ($p<0.01$). On the other hand, a significant correlation was also found between Y_D and indices such as DI ($p<0.01$), SSI, and YSI ($p<0.05$). Significant correlations of Y_N and Y_D with GMP, MP, HM, STI, YI, and SNPI also support the previous findings on the correlations between yield under drought and normal conditions with the above indices in sesame and other crops (Boureima et al. 2016; Mau et al. 2019; Mickky et al. 2019). It was suggested that indices correlated with both Y_N and Y_D are suitable for selection under water deficit (Mitra 2001). As previously described, drought tolerance is the ability of a plant to sustain production with minimal reduction (yield stability) under stress conditions. However, GMP, MP, and STI indices place more emphasis on yield potential which may cause a bias error if the difference between Y_N and Y_D is large (Moosavi et al. 2008; Farshadfar and Elyasi 2012). Therefore, they might recommend genotypes that have high yield potential but not necessarily for high drought-tolerance and are highly prone to reduced yield under water stress. On the other hand, indices such as TOL, YSI, and SSI must be considered for selecting stable genotypes under drought stress (Moosavi et al. 2008; Farshadfar and Elyasi 2012). Many a times, using above mentioned indices may lead to selection of genotypes with low Y_N (low yield potential) however, these indices may be suitable for biological studies of drought tolerance. From the agricultural and commercial perspectives point of view, high yield under non-stress conditions is equally important (Moosavi et al. 2008). To conclude, the indices SNPI, YI, and DI and to some extent, TOL, YSI, and SSI should be used in breeding programs for drought tolerance which consider both yield potential and stability (Moosavi et al. 2008; Farshadfar and Elyasi 2012) genetic parameters.

Multivariate analysis

PCA, a multivariate statistical method was used to assessment genotypes and indices more accurately under drought conditions. The result of PCA showed that only the first two principal components (PC) had an eigenvalue greater than 1, which together explained 99.62% of the variance (Supplementary Fig. S1). The Varimax rotation method with Kaiser normalization procedures were used for easier interpretation following PCA (only PCs with eigen values greater than 1 were rotated). The two rotated components (RC) obtained after Varimax rotation explained 67.66 and 31.96% of total variation for drought tolerance indices among genotypes, respectively. The squared cosines among RCs and indices suggested that the Y_N, Y_D, GMP, MP, HM, STI, YI, and SNPI were related to RC1 (Table 6). The correlation of RC1 with all these related indices was positive. The RC1 also showed a positive correlation with TOL and DI indices. Since the indices belonging to this component are highly related to yield under both conditions, RC1 can be called the yield potential component. On the other hand, the SSI, TOL, YSI, and DI seems be related to RC2 due to the higher squared cosines among them (Table 6). However, SSI and TOL showed a negative correlation with RC2, while YSI and DI showed a positive one. As mentioned earlier, these indices are associated with yield stability and relative tolerance. Therefore, RC2 can be called the yield stability component.

The PCA results after Varimax rotation were visualized by a biplot to better interpret the relationships among drought tolerance indices and genotypes (Fig. 1). Genotypes with higher RC1 scores expected to have higher yield potential, while those with higher RC2 scores expected to have higher yield stability. Accordingly, G04, G07, and G13 are the most suitable genotypes for studies on the biological basis of drought tolerance and conversely, G02 and G15 genotypes are the best for drought susceptibility studies. G05, G01 and G11, which have the highest yield potential, are the most suitable genotypes for cultivation under normal conditions, while also providing acceptable yield in the face of drought stress. Since showed high scores in both RC1 and RC2, G04 and G01 are the most appropriate genotypes to cultivate under water deficit, which also have high potential to use in commercial breeding programs. Among indices, YI, SNPI, and DI that had relatively large loading on both RC1 and RC2 (high relation with both yield potential and stability) are suggested as the most appropriate index for selection under drought stress. Previous studies also placed SNPI and YI among the most appropriate indices for screening drought-tolerance cultivars, which was consistent with the results of present study (Farshadfar et al. 2012; Boureima et al. 2016; Mau et al. 2019).

The WPGMA clustering method was used to group the genotypes based on Y_N, Y_D, and drought tolerance indices values. The genotypes were clustered into three distinct groups (Fig. 2). The first group included, G01, G04, G05, and G11 genotypes; the second group included G02, G03, G06, G07, G12, G13, and G15 genotypes; and the third group included G08, G09, G10, and G14 genotypes. The first group that had the highest mean values for most of drought tolerance indices, was classified as high drought-tolerant genotypes (Supplementary Table S3). The second group, which had lower indices values compared to the first ones, was considered as moderate drought-tolerant genotypes. The third group was named drought-sensitive genotypes due to having the lowest indices values. Similar to us, cluster analysis has been commonly used in drought stress studies to classify and determine tolerant or susceptible cultivars (Mickky et al. 2019). Overall, the genotypes classified as the most tolerant ones by cluster analysis more or less correspond to those identified in the previous sections.

The present findings showed noticeable variation for drought tolerance among sesame genotypes used for analysis. Due to high heritability and strong positive correlations with yield, the number of capsules and capsule diameter were suggested as potential criteria for selection under drought stress. Based on the results, SNPI, YI, and DI were suggested as the most appropriate indices to evaluate sesame genotypes under drought conditions. The genotypes, Chinese (G01), Naz Chand Shakhe (G05), and Darab1 (G04) emerged as suitable tolerant genotype for commercial cultivation as well as for breeding programs. Moreover, Darab1 (G04) and Moghan17 (G02) were suggested to study biological aspect of drought tolerance and sensitivity, respectively. Overall, the evaluation criteria proposed in this study can be used for the efficient selection of drought-tolerant genotypes in sesame.

Supplementary materials

Supplementary Tables S1 to S3 and Supplementary Fig. 1 are provided in this article.

Authors' contribution

Conceptualization of research (MAB, SKK, AD, PM, HNZ); Designing of the experiments (MAB, SKK, AD, PM, HNZ); Sharing of experimental materials (SKK, AD); Execution of field/lab experiments and data collection (MAB); Analysis of data and interpretation (MAB); Preparation of the manuscript (MAB, AD).

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Supplementary Table S1. Means of morphological traits of sesame genotypes under normal and drought conditions

Condition	Genotype	Traits						
		Plant Height (cm)	No. of Capsules	Stem Diameter (cm)	Capsule Diameter (cm)	Seeds per Capsule	100-Seed Weight (g)	Yield per Plant (g)
Normal	G01	111.11	46.11	4.56	8.32	15.28	0.28	11.44
	G02	118.33	60.78	4.22	8.00	16.39	0.27	12.47
	G03	90.56	57.22	4.51	7.78	18.17	0.28	11.23
	G04	104.89	54.78	4.02	5.92	16.39	0.26	9.17
	G05	138.56	51.78	4.02	6.06	20.17	0.30	12.43
	G06	118.67	47.33	3.60	6.41	17.61	0.29	9.53
	G07	119.67	46.00	4.39	6.28	17.61	0.28	8.76
	G08	114.44	37.56	3.61	5.94	18.50	0.30	8.59
	G09	106.56	29.33	4.12	6.64	17.50	0.29	6.27
	G10	102.44	40.22	3.90	5.50	16.94	0.24	6.21
	G11	100.78	57.11	4.57	6.72	19.39	0.27	11.64
	G12	109.33	50.67	4.48	6.68	18.28	0.30	10.69
	G13	90.56	48.00	4.47	6.67	17.61	0.28	9.42
	G14	124.44	31.56	5.02	4.78	15.83	0.30	6.35
	G15	111.33	47.11	4.10	5.74	19.61	0.28	10.97
	Mean	110.78	47.04	4.24	6.50	17.69	0.28	9.68
Drought	G01	104.56	28.56	4.50	8.38	13.00	0.26	6.85
	G02	104.56	29.44	3.60	5.76	13.89	0.27	5.47
	G03	88.11	31.56	4.38	6.01	14.44	0.27	5.97
	G04	99.33	35.67	3.96	5.81	15.22	0.27	6.81
	G05	118.33	32.00	3.69	5.59	16.56	0.27	6.88
	G06	98.56	26.44	3.42	5.48	14.78	0.26	5.10
	G07	105.44	24.56	3.79	5.94	16.89	0.29	5.84
	G08	81.89	18.44	3.37	4.09	14.33	0.21	3.25
	G09	93.67	12.78	3.16	5.28	16.00	0.27	3.18
	G10	86.11	22.00	3.47	5.69	12.78	0.25	3.85
	G11	90.67	34.89	4.07	5.86	16.22	0.24	6.56
	G12	84.22	27.33	4.34	6.08	15.11	0.26	5.43
	G13	83.78	28.67	4.38	6.34	15.56	0.26	5.84
	G14	87.22	13.00	4.83	4.26	15.33	0.29	3.38
	G15	89.33	18.33	3.76	5.90	15.89	0.28	4.38
Mean		94.39	25.58	3.91	5.76	15.07	0.26	5.25
LSD (P <0.05)		8.64	5.40	0.50	0.71	1.46	0.02	1.80
Reduction Ratio (%)		14.80	45.62	7.66	11.26	14.81	6.40	45.73

Supplementary Table S2. Ranking of sesame genotypes based Y_N, Y_D, and drought tolerance indices

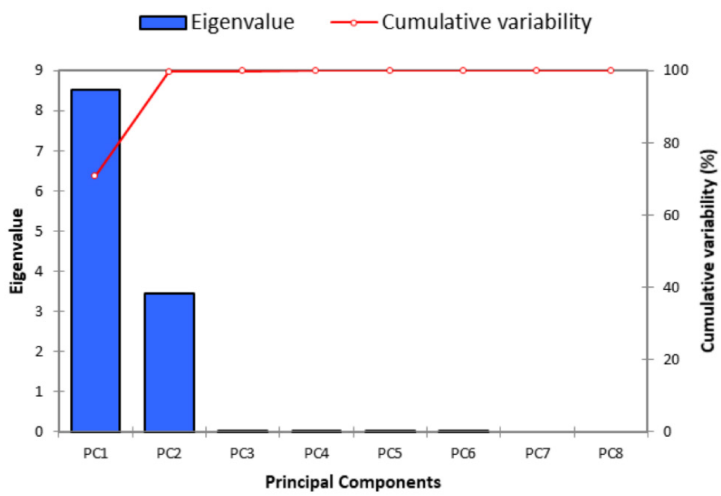
Genotype	Y_N		Y_D		SSI		GMP		MP		HM		TOL		STI		YI		YSI		DI		SNPI		$\bar{R}$
	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	
G01	11.44	4	6.85	2	0.88	5	8.85	2	9.15	2	8.57	2	4.58	8	0.84	2	1.30	2	0.60	5	0.78	2	12.90	2	3.2
G02	12.47	1	5.47	8	1.23	13	8.26	4	8.97	4	7.60	6	6.99	15	0.73	4	1.04	8	0.44	13	0.46	10	9.85	9	7.9
G03	11.23	5	5.97	5	1.02	9	8.19	5	8.60	5	7.79	5	5.26	10	0.72	5	1.14	5	0.53	9	0.60	7	10.94	7	6.4
G04	9.17	10	6.81	3	0.56	1	7.90	6	7.99	7	7.82	4	2.36	2	0.67	6	1.30	3	0.74	1	0.96	1	14.23	1	3.8
G05	12.43	2	6.88	1	0.98	7	9.25	1	9.65	1	8.86	1	5.55	13	0.91	1	1.31	1	0.55	7	0.73	4	12.70	3	3.5
G06	9.53	8	5.10	10	1.02	8	6.98	10	7.32	10	6.65	10	4.43	7	0.52	10	0.97	10	0.54	8	0.52	9	9.36	10	9.2
G07	8.76	11	5.84	7	0.73	2	7.15	9	7.30	11	7.01	9	2.93	3	0.55	9	1.11	7	0.67	2	0.74	3	11.42	5	6.5
G08	8.59	12	3.25	14	1.36	15	5.28	12	5.92	12	4.72	13	5.34	12	0.30	12	0.62	14	0.38	15	0.23	15	5.86	14	13.3
G09	6.27	14	3.18	15	1.08	11	4.47	15	4.73	15	4.22	15	3.09	5	0.21	15	0.61	15	0.51	11	0.31	14	5.79	15	13.3
G10	6.21	15	3.85	12	0.83	3	4.89	13	5.03	13	4.76	12	2.36	1	0.26	13	0.73	12	0.62	3	0.46	11	7.33	12	10.0
G11	11.64	3	6.56	4	0.96	6	8.74	3	9.10	3	8.39	3	5.09	9	0.81	3	1.25	4	0.56	6	0.70	5	12.14	4	4.4
G12	10.69	7	5.43	9	1.08	12	7.62	7	8.06	6	7.20	8	5.27	11	0.62	7	1.03	9	0.51	12	0.52	8	9.88	8	8.7
G13	9.42	9	5.84	6	0.83	4	7.42	8	7.63	9	7.21	7	3.58	6	0.59	8	1.11	6	0.62	4	0.69	6	11.10	6	6.6
G14	6.35	13	3.38	13	1.02	10	4.63	14	4.86	14	4.41	14	2.97	4	0.23	14	0.64	13	0.53	10	0.34	12	6.18	13	12.0
G15	10.97	6	4.38	11	1.31	14	6.93	11	7.68	8	6.26	11	6.58	14	0.51	11	0.83	11	0.40	14	0.33	13	7.89	11	11.3

Y_N: average yield per plant under normal condition; Y_D: average yield per plant under drought condition; SSI: Stress Susceptibility Index; GMP: Geometric Mean Productivity; MP: Mean Productivity; HM: Harmonic Mean; TOL: Tolerant Index; STI: Stress Tolerant Index; YI: Yield Index; YSI: Yield Stability Index; DI: Drought Resistance Index; SNPI: Stress Non-Stress Production Index; R: Average Rank.

Supplementary Table S3. Means of Y_N, Y_D, and drought tolerance indices in sesame genotype groups obtained from cluster analysis

Group	Y_N	Y_D	SSI	GMP	MP	HM	TOL	STI	YI	YSI	DI	SNPI
1	11.17	6.78	0.84	8.69	8.97	8.41	4.39	0.81	1.29	0.61	0.79	12.99
2	10.44	5.43	1.03	7.51	7.94	7.10	5.01	0.60	1.03	0.53	0.55	10.06
3	6.85	3.42	1.07	4.82	5.14	4.53	3.44	0.25	0.65	0.51	0.33	6.29

Y_N = Average yield per plant under normal condition; Y_D= Average yield per plant under drought condition; SSI = Stress Susceptibility Index; GM = Geometric Mean Productivity; MP = Mean Productivity; HM = Harmonic Mean; TOL = Tolerant Index; STI = Stress Tolerant Index; YI = Yield Index; YSI = Yield Stability Index; DI = Drought Resistance Indexand SNPI = Stress Non-Stress Production Index



Supplementary Fig. S1. Eigen values and cumulative variances of principal components (PC) of PCA on estimated drought tolerance indices among sesame genotypes