ANALYSIS OF DROUGHT-TOLERANT GENOTYPES IN SORGHUM USING MULTIVARIATE ANALYSIS TECHNIQUES

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ABSTRACT

This study was conducted during the spring and fall seasons of 2024. The results showed a significant positive correlation between the three indices and productivity under both drought stress conditions (Ys) and non-stress conditions (Yp). This indicates that these indices are effective in identifying Genotype with high productivity potential in both scenarios. In the spring season, the superior Genotype were G7 (Giza 113), G14 (ACSAD 51), G15 (ACSAD 56), G20 (ACSAD 62), and G23 (ACSAD 66). In fall season, the top-performing Genotype were G8 (Tabet), G10 (Uruk), G17 (ACSAD 47), G20 (ACSAD 58), and G25 (ACSAD 68). All these Genotype demonstrated drought tolerance with high productivity under both stressed and non-stressed conditions. The indices used in this study help in identifying Genotype with a high ability to withstand drought, thus enhancing their effectiveness in challenging environmental conditions. Additionally, the aforementioned Genotype are considered suitable for use in crop improvement *programs* in the central region of Iraq, due to their ability to adapt to drought conditions and maintain good productivity under varying circumstances.

Keywords: Stress indices, PCA, Cluster Analysis, Rank Summation, Drought Indices Correlation

تحليل التراكيب الوراثية المتحملة للجفاف في الذرة البيضاء باستعمال أساليب تحليل المتغيرات المتعدد

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المستخلص:

هدف البحث تقييم قدرة التراكيب الوراثية من الذرة البيضاء على تحمل الجفاف. ومن ناحية العلاقة بين المعايير والإنتاجية تمت الزراعة في الموسم الربيعي والخريفي 2024 أظهرت النتائج أن المعايير الثلاثة المذكورة مرتبطة ارتباطاً موجبا ومعنوياً بالإنتاجية تحت ظروف الجفاف (Ys) وظروف عدم الجفاف (Yp). وهذا يشير إلى أنها فعالة في تشخيص التراكيب الوراثية ذات القدرة الإنتاجية العالية في كلا الحالتين. اما لتحديد التراكيب الوراثية المتفوقة كانت في الزراعة الربيعية: التركيب الوراثي (G7 (Giza 113 والتركيب الوراثي G14 ACSAD 51 والتركيب الوراثي (G15 (ACSAD 56 والتركيب الوراثي (G20 (ACSAD 62 و(G 23ACSAD 66) اما في الزراعة الخريفية فقد تفوق التركيب الوراثي (G8 (Tabet و التركيب الوراثي (G10 (Uruk و التركيب الوراثي (G 17 (ACSAD 47 و التركيب الوراثي (G20 (ACSAD 58 والتركيب الوراثي (G25 (ACSAD 68. جميع هذه التراكيب أظهرت قدرة على تحمل الجفاف مع قابلية إنتاجية عالية في ظروف الإجهاد وعدم الإجهاد، ان المعايير المستخدمة تساعد في تحديد التراكيب الوراثية التي تتميز بقدرة عالية على تحمل الجفاف، مما يعزز من فاعليتها في الظروف البيئية الصعبة. وكذلك التراكيب الوراثية المذكورة تعتبر مناسبة للاستخدام في تحسين المحاصيل الزراعية في المنطقة الوسطى من العراق، نظراً لقدرتها على التأقلم مع الجفاف وتحقيق إنتاجية جيدة في ظل ظروف مختلفة.

كلمات مفتاحية: ادلة الاجهاد، تحليل المكون الرئيس، التحليل العنقودي، مجاميع الرتب. ارتباط ادلة الجفاف.

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INTRODUCTION

sorghum (*Sorghum bicolor*) production reached 60.2 million tons in (9), with a cultivated area of 33.97 million hectares. Sorghum production is influenced by various environmental factors, particularly water availability, including temperature, drought periods, soil diversity, and humidity levels, all of which affect the growth and productivity of the crop. Additionally, the genetic resources of the crop play a vital role in determining its productivity. The quality of genetic varieties is essential for improving yields. Genetic erosion and the degeneration of varieties can lead to reduced productivity, necessitating the improvement of genetic resources for better performance. Advancements in these areas could help increase sorghum productivity in Iraq, leading to a significant rise in production that could meet the local market demand. Sorghum is particularly sensitive to water stress, especially when this stress coincides with the flowering period. Such stress can lead to significant yield losses, ranging from 40% to 55%, highlighting the urgent need to develop drought-tolerant Genotype to improve productivity (1, 3) Ongoing research aimed at improving genetic resources and agricultural techniques to enhance water-use efficiency and productivity under dry conditions is essential. By applying these strategies, the resilience of sorghum to arid conditions can be enhanced, leading to a significant increase in productivity. The provided information highlights how drought-tolerant Genotype can be identified using a variety of methods and approaches to evaluate their performance under water stress and non-stress conditions. Here is a detailed and comprehensive analysis of the topic: Among the methods for distinguishing Genotype, some researchers have used mathematical equations to compare the productivity performance of genotypes under stressed and non-stressed conditions. These approaches help evaluate how water stress affects productivity, select genotypes with optimal performance, and assess yield loss. Most plant breeders focus on the percentage decrease in yield due to stress, as this is considered a key indicator of a genotype's ability to adapt to stress conditions. Drought tolerance and adaptation may arise from factors of acclimatization rather than from drought resistance alone. (2,15,17) This suggests that adaptation to environmental conditions might be more complex than merely enduring water stress. As an indicator of drought tolerance, yield loss is often used to measure the decrease in yield under drought conditions compared to non-stressed conditions. These indicators provide an objective measure of the Genotype' ability to adapt to drought. Additionally, reports indicate that these drought tolerance indicators are correlated with the Genotype' capacity to withstand drought, supporting the effectiveness of these indicators in diagnosing drought-tolerant genotypes. Genotype can be classified according to their response to stress. Fernandez classified the response of sorghum genotypes based on two sets of conditions (stress and non-stress) into four groups Group A consists of genotypes that achieve higher-than-average productivity in both stressed and non-stressed conditions. These genotypes are considered excellent performers as they achieve good productivity in both normal and harsh conditions. Group B consists of genotypes that perform better than average only under non-stressed conditions. Genotypes under stress conditions. Furthermore, ongoing research and development in improving Genotype and assessing their response to water stress can contribute to enhancing agricultural productivity under harsh conditions. By applying these strategies, crops like sorghum can be made more resilient to water stress, thereby improving productivity and increasing the effectiveness of water resource utilization (13,14). Selection based on the combination of various drought tolerance indicators can provide criteria for improving stress tolerance in several agricultural crops. Additionally, studying the correlation coefficient is important and useful for determining the degree of linear relationship between the indicators used to identify drought-tolerant Genotype. Principal Component Analysis (PCA), which is one of the techniques used to summarize and reduce data, transforms a large number of inherently related variables, at least partially, into a much smaller set of independent variables. These are usually referred to as the principal components, and they are primarily calculated from the original variables in proportions and magnitudes that vary depending on the role and impact of each *variable*. (18, 19). The aim of this study is to diagnose drought-tolerant sorghum genotypes under the conditions of the central region of Iraq. It also seeks to determine the efficiency of drought indices or indicators used to diagnose drought-tolerant or drought-sensitive genotypes and to interpret the relationship between the drought indices used through multivariate analysis, including Principal Component Analysis (PCA) and Cluster Analysis.

MATERIALS AND METHODS

To achieve the objectives of this study, a field experiment was conducted at a farmer's experimental field in Al-Anbar Governorate during the spring and fall seasons of 2023. A split-plot design was used in a randomized complete block design (RCBD) with three replications. The Genotype (G) were assigned to the subplots, while the main plots represented the irrigation treatments (S). The irrigation treatments included Yp, which represents an irrigation interval of 5 days, and Ys, which represents an irrigation interval of 10 days. The grains were sown on March 24, 2024, for the spring season, and on July 23, 2024, for the fall season. The experimental unit area was (4×3) m, consisting of four rows each 3 meters long, with a distance of 75 cm between rows and 25 cm between plants. The distance between experimental units was one meter, with a 2-meter between replications. The plant density was 53,333 plants per hectare. Urea fertilizer (46% N) was applied at a rate of 400 kg N·ha^{1-}in three equal doses: the first at planting, the second when the plants reached a 25 cm height, and the third at the beginning of flowering. Triple superphosphate fertilizer (46% P2O5) was applied at a rate of 200 kg P2O5·ha $^{-1}$ in one dose, mixed with the soil along the planting rows. ======Genetic Materials This study included 25 Genotype (20 genotypes of sorghum and 5 approved cultivars), as detailed in Table (1).

Table 1. Genotype used in the study

Code	Genotype	Code	Genotype
G1	Inqath	G14	ACSAD 51
G2	Rabeh	G15	ACSAD 56
G3	Ishtar	G16	ACSAD 57
G4	Lilo	G17	ACSAD 58
G5	Mabrok	G18	ACSAD 60
G6	Kavir	G19	ACSAD 61
G7	Giza 113	G20	ACSAD 62
G8	Tabet	G21	ACSAD 63
G9	Babel	G22	ACSAD 65
G10	Uruk	G23	ACSAD 66
G11	ACSAD 5	G24	ACSAD 67
G12	ACSAD 36	G25	ACSAD 68
G13	ACSAD 47		

Irrigation Method and Water Quantity Calculation: Irrigation was conducted using plastic pipes connected to a pump equipped with a flow meter to measure the amount of water applied to each experimental unit. Equal amounts of water were supplied from a reservoir measuring 4×5 meters with a depth of 2 meters for the plots at planting. The pump discharge rate was 50 liters per second. In the first treatment, irrigation was done every 5 days, while in the second treatment, irrigation was done every 10 days, referred to as Yp and Ys, respectively, for the two experiments. The total water quantity applied during the spring and fall seasons was calculated. For the Yp treatment, 21 irrigations were applied, with a total water quantity of 866.86 mm. For the Ys treatment, 13 irrigations were applied, with a total water quantity of 458.60 mm during the spring season. Data Collection and Analysis After harvesting the two middle rows, each 2 meters long, with a net harvested area of 4 m², the heads of the sorghum plants were collected, threshed, and weighed. The total grain yield was calculated and converted into tons per hectare. The results were analyzed statistically using analysis of variance (ANOVA). Additionally, drought indices were calculated and ranked (Table) using MS Excel. The correlation coefficient between yield (Yp and Ys) and drought indices was also calculated. Multivariate analysis, including principal component analysis (PCA) and cluster analysis, was performed using the GenStat 12 and Minitab 15 software programs to diagnose and classify the genetic lines as drought-sensitive or drought-tolerant. (4). The means compound using L.S.D 0.05.

Drought Tolerance Indices

The drought indices were calculated based on the mathematical relationships provided in Table (2).

Table 2. Drought Indices, Symbols, Mathematical Equations, and Sources

	Drought Index	Symbol	Mathematical Equation
1	**Mean Productivity**	**MP**	$MP = (Y_p + Y_s)/2$
2	**Stress Tolerance**	**TOL**	$TOL = Y_p - Y_s$
3	**Stress Susceptibility Index**	**SSI**	$SSI = [1-(Y_s/Y_p)]/1-(\bar{Y}_s/\bar{Y}_p)$
4	**Geometric mean Productivity**	**GMP**	$GMP = \sqrt{Y_p * Y_s}$
5	**Stress Tolerance Index**	**STI**	$STI = (Y_p x Y_s)/\bar{Y}_p^2$
6	**Relative drought index**	**RDI**	$RDI = (Y_S/Y_P)/(\bar{Y}_S/\bar{Y}_P)$
7	**Ranksum**	**RS**	$RS = \text{Rank Mean}(\bar{R}) + \text{Rank SD}$

- **Yp and Ys represent the grain yield under 25% and 75% depletion of available water, respectively.**
- **The average grain yield of the genetic compositions under 25% and 75% depletion of available water, respectively.**
- **SD: Standard deviation of ranks.**

RESULTS AND DISCUSSION

The results of the analysis of variance for the spring and fall seasons showed a significant effect of irrigation treatments, genotypes, and their interaction. Highly significant differences were found for irrigation intervals for both the spring and fall seasons. Additionally, there were highly significant differences for the mean values of the genotypes, and the interaction between irrigation treatment and genotypes was also highly significant (Table 3).

Table 3. Mean Squares for Analysis of Variance of Grain Yield for 24 Genotypes under 5-day Irrigation Interval (Yp) and 10-day Irrigation Interval (Ys)

Source of Variation	df	Mean Square	
		Spring Season	Fall Season
Block	2	1923.2	0.215
Stress Level	1	22319.6**	18331.35**
Error (a)	2	86.2	53.3
Genotypes	23	3971.53**	4415.82**
Stress * Genotypes	24	20085.64**	12299.07 **
Error (b)	96	22.24	38.66
Total	149		

(Note: The exact values for Mean Squares **and** F-Values **need to be filled in based on the actual statistical output.)**

These results confirm that both irrigation management and genotype play a crucial role in the productivity of sorghum. The significant interaction indicates that the performance of the genotypes is influenced by the irrigation intervals, emphasizing the need for selecting drought-tolerant genotypes that can maintain good productivity under water stress conditions. The significant differences in genotypes also highlight the potential for genetic improvement in terms of drought tolerance and productivity under different irrigation regimes.The results of the statistical analysis, presented in Table (4), indicated significant differences between the mean values of irrigation intervals, sorghum genotypes, and their interactions for the trait of single-plant yield in both the spring and fall seasons. Table (3) shows that there was significant variation among the genotypes. The genotype G9 achieved the highest mean yield, reaching 111.7 g, with no significant difference from genotypes G14, G5, G3, and G20. On the other hand, genotype G23 showed the lowest mean of 52.50 g for the spring season. For the fall season, genotype G10 had the highest mean yield of 116.95 g, and there was no significant difference from genotypes G9, G25, G20, G16, and G5. The results also show that plants irrigated with a 5-day interval (Yp) performed significantly better in terms of single-plant yield, with mean values of 121.19 g and 128.29 g for the spring and fall seasons, respectively. However, the grain yield dropped nearly by half under the 10-day irrigation interval (Ys), with a mean yield of 54.56 g and 59.03 g for the spring and fall seasons, respectively. The decreases in grain yield under drought conditions can be attributed to the adverse effects on plant growth and development. The long 10-day irrigation interval likely influenced all yield components significantly, resulting in abortion of small, shriveled, and deformed grains due to accelerated maturity and reduced grain filling duration. Water stress also reduced the translocation of photosynthetic materials to fertilized grains, leading to fewer grains and smaller, underdeveloped grains. Moreover, water stress resulted in earlier flowering, which shortened the growth stages and forced plants to complete their life cycle and grain production in a shorter time frame. These findings are consistent with previous studies that indicated a significant reduction in grain yield of plants exposed to water stress, which was attributed to smaller ear sizes, fewer grains per ear, and reduced grain weight. The statistical analysis also revealed a significant interaction between the two factors, suggesting that the behavior of the genotypes changed according to the irrigation intervals, especially under the 10-day interval (water stress). The decline in yield under the 10-day irrigation interval was acceptable, despite the extended period, because the plants appeared to be somewhat drought-tolerant, possibly due to lower-than-average temperatures, which helped the plants tolerate the stress.(5,6,12, 19,20) It was noted that the interaction involved a difference in the magnitude of response rather than a directional change. That is, all genotypes showed a reduction in grain yield when subjected to the 10-day irrigation interval compared to the 5-day interval across both seasons. The response of the genotypes to changes in irrigation days was significant. Genotype G14 utilized the optimal irrigation days efficiently, as it achieved the highest yield (142.4 g) under the 5-day irrigation treatment, showing no significant difference from 10 other genotypes. In contrast, other genotypes, such as G23, G21, and G1, had a different response under the 10-day irrigation treatment, recording the lowest mean values of 30.0 g, 33.4 g, and 39.3 g, respectively, in the spring season. In the fall season, genotype G14 again demonstrated efficient use of the 5-day irrigation treatment, achieving the highest yield of 152.8 g, with no significant difference from 10 other genotypes. Conversely, genotypes G21, G6, and G15 had a different response under the 5-day treatment, with lower yields of 39.3 g, 41.4 g, and 43.1 g, respectively. These results are in agreement with previous studies by (15,17,21), which showed similar findings regarding the impact of water stress on yield reduction and the differential response of genotypes to varying irrigation schedules.

Table 4. Mean plant grain yield (g) for Sorghum genotypes for an irrigation interval of 5 days to an irrigation interval of 10 days for the spring season 2024 and the fall season 2024

Genotypes	Spring Season			Fall Season		
	5 Days	10 Days	Mean	5 Days	10 Days	Mean
G 1	97.0	39.3	68.15	89.5	43.9	66.70
G 2	130.5	60.1	93.30	126.6	59.0	92.80
G 3	135.2	65.8	100.50	132.4	61.2	96.80
G 4	118.9	57.0	87.95	94.5	46.7	70.60
G 5	138.1	65.3	101.70	142.7	67.9	105.30
G 6	134.9	54.9	94.90	137.5	41.4	89.45
G 7	112.7	63.3	88.00	122.8	65.6	94.20
G 8	119.0	85.5	88.75	131.3	61.1	96.20
G 9	145.3	78.1	111.7	143.6	7105	107.55
G 10	134.0	55.4	69.20	146.7	78.2	116.95
G 11	107.4	51.8	79.60	116.8	50.1	83.45
G 12	124.7	59.5	92.10	122.9	52.6	78.58
G 13	102.3	54.4	78.35	115.2	57.3	86.52
G 14	142.4	63.4	102.90	152.8	56.7	104.75
G 15	115.0	44.5	79.75	112.3	43.1	77.70
G 16	124.1	55.1	89.60	141.5	66.7	104.10
G 17	140.6	54.0	97.30	136.6	68.3	102.45
G 18	119.6	46.5	83.05	112.8	59.3	91.5
G 19	131.5	60.3	95.90	139.3	69.0	104.15
G 20	132.6	67.1	99.58	145.8	65.5	105.65
G 21	78.7	33.4	56.05	124.6	39.3	81.95
G 22	123.5	41.8	82.65	136.5	66.7	101.60
G 23	74.7	30.3	52.50	81.2	46.0	63.60
G 24	127.1	50.6	88.85	145.6	61.6	103.60
G25	117.1	53.7	85.40	144.2	68.1	106.15
Mean	121.196	54.56		128.29	59.03	
LSD 5%	Irrigation Days	11.88			13.19	
	Genotypes	12.51			13.32	
	Interaction	17.78			18.84	

Six criteria or indices, used by several researchers, were calculated based on the grain yield under drought conditions (Ys) and non-drought conditions (Yp). (3) confirmed that the appropriate criterion is one that has a positive correlation with yield in both stress and non-stress conditions. Based on the MP index (mean yield of Yp and Ys), the genetic lines G7, G14, G15, G21, and G23 were classified as drought-tolerant in the spring season, while G17, G13, G10, G7, and G25 were classified as drought-tolerant in the fall season. The genetic lines G14, G6, G1, G18, and G19 were classified as drought-sensitive for both seasons (Table 5). Since the MP index relies on the arithmetic mean, there may be a bias due to the relative difference between Yp and Ys yields, which can be influenced by outliers. This index does not distinguish genetic lines with high yield potential under both Yp and Ys but includes those with high yield potential in either Yp or Ys. To overcome this bias, the geometric mean productivity (GMP) index was suggested, which is preferred by plant breeders interested in relative yield and is less sensitive than MP to the differences between Yp and Ys. Based on the results obtained from the classification of genetic lines according to this index, G18, G13, G4, G21, G24, G23, and G22 were classified as drought-tolerant for both seasons, while G17, G14, G9, and G19 were classified as drought-sensitive for both seasons (Table 5). These results are consistent with those obtained using the MP index. Abd El-Mohsen *et al* (2) suggested that selection based on GMP could be more efficient in identifying drought-tolerant genetic lines in bean crops. Based on the drought tolerance index (STI), which is calculated from GMP, the smaller the difference in yield between irrigation treatments (Yp and Ys), the higher the STI value, indicating greater drought tolerance. Conversely, a larger yield difference results in a smaller STI value, indicating lower drought tolerance. It is clear from this that genetic lines

G19, G17, G13, and G23 were classified as drought-tolerant in both the spring and fall seasons, while G22, G18, G12, and G24 were classified as drought-sensitive for both seasons (Table 5). Other genetic lines were classified as semi-tolerant or semi-sensitive to drought. These results are consistent with the classifications obtained using GMP and MP. It is evident that the indices STI, GMP, and MP are comparable in classifying genetic lines with high yield potential under both Yp and Ys, identifying those belonging to the first group in Fernandez's classification (group A), which is characterized by high yield potential in both Yp and Ys. According to the Stress Susceptibility Index (SSI) proposed by (11,18), which is based on the yield under stress as a function of the yield under non-stress conditions, selection based on this index favors genetic lines with high yield under non-stress (Yp) and low yield under stress (Ys). This would select genetic lines belonging to the second group (B) in Fernandez's classification, which are characterized by high yield potential under non-stress conditions. From Table 5, it is clear that genetic lines G20, G17, G12, and G21 were classified as drought-sensitive in both the spring and fall seasons, while G22, G19, G14, and G23 were classified as drought-tolerant for both seasons. Selection based on SSI values would result in the selection of genetic lines with low yield potential under Ys and high yield potential under Yp. The values of SSI range from 0 to 1, and higher values indicate greater sensitivity to drought. The main drawback of this index is its inability to distinguish between genetic lines in group A (with high yield potential under both conditions) and group C (with low yield potential under both conditions), as explained by Clarke et al. Moreover, SSI does not differentiate between drought-tolerant genetic lines and those with inherently low yield potential. The Stress Tolerance Index (TOL), which is based on the difference in yield between stress (Ys) and non-stress (Yp) conditions, indicates that higher values of this index correspond to higher sensitivity to drought. This would favor genetic lines with high yield under non-stress conditions (Yp) and low yield under stress conditions (Ys). Based on this index, genetic lines G17, G13, G7, G20, and G24 were classified as drought-sensitive for both the spring and fall seasons, while G18, G16, G12, and G21 were classified as drought-tolerant for both seasons. The Relative Drought Index (RDI), which classifies genetic lines belonging to group C in Fernandez's classification (those that are associated with their yield potential in drought conditions Ys), was used to assess drought tolerance. The genetic lines G20, G13, G11, G22, and G23 were classified as drought-tolerant for both the spring and fall seasons, while G17, G12, G10, G21, G19, and G18 were classified as drought-sensitive in the spring season (Table 5).

Table 5. Drought Indices and Rankings of Twenty-Five Genetic Lines Under Drought (Ys) and Non-Drought (Yp) Conditions for the Spring and Fall Seasons of 2024

							MP	GMP	STI	SSI	TOL	RDI
Tolerant	**Spring**	**Fall**	**Spring**	**Fall**	**Spring**	**Fall**	**Spring**	**Fall**	**Spring**	**Fall**	**Spring**	**Fall**
genotypes	G3	G3	G3	G2	G9	G7	G7	G10	G7	G7	G7	G12
	G5	G5	G7	G8	G14	G10	G14	G13	G12	G10	G14	G14
	G9	G9	G8	G16	G15	G17	G15	G15	G16	G13	G15	G16
	G7	G10	G14	G17	G19	G19	G19	G19	G18	G18	G20	G21
	G8	G16	G20	G19	G20	G20	G22	G22	G21	G21	G22	G22
	G14	G20	G22	G21	G23	G22	G23	G23	G25		G24	G23
	G19	G25	G24	G23	G25	G25						
Sensitive	G3	G3	G3	G2	G4	G9	G10	G2	G6	G5	G5	G1
genotypes	G8	G11	G9	G10	G12	G12	G12	G12	G14	G7	G9	G6
	G11	G13	G10	G12	G14	G16	G17	G15	G18	G13	G12	G14
	G16	G17	G14	G17	G18	G18	G18	G17	G19	G17	G14	G17
		G20	G17	G19	G22	G22	G20	G20	G25	G19	G17	G19
		G24	G19	G19	G24	G24	G21	G21		G20	G19	19
				G25			G24			G24	G22	G21

Correlation Coefficient Between Drought Indices: In order to identify the desired drought indices for plant breeders to diagnose the lines and hybrids with a higher drought tolerance capacity, the characteristics mentioned by (10) were used. These characteristics are distinguished by a positive and high correlation with grain yield under irrigation intervals of 12 days (drought stress, Ys) and 6 days (non-drought, Yp). Therefore, the correlation between yield under irrigation intervals of 5 and 10 days with the drought indices was calculated. Tables (6) and (7) show that the grain yield under drought stress (Ys) is positively correlated with the yield under non-drought conditions (Yp), with correlation coefficients of 0.94 and 0.82 for the spring and fall seasons, respectively. This suggests that selection based on high productivity under the 5-day irrigation interval (Yp) could be go result in genetic lines with high productivity under the 10-day irrigation interval (Ys), which is consistent with the results obtained by (3,5,6,16,19) The grain yield (Yp and Ys) was positively correlated with the drought indices GMP, STI, and MP in both seasons, confirming the ability of these indices to diagnose genetic lines with high productivity under both Yp and Ys conditions. These are the indices that plant breeders rely on. The drought index TOL was positively correlated with Yp (0.98 and 0.83) for the spring and fall seasons, respectively. However, the correlation between TOL and Ys was negative (-0.44 and -0.49) for both seasons, indicating that TOL is effective in identifying genetic lines with high productivity only under non-drought conditions (Yp). The yield under drought stress (Ys) was negatively correlated with the Stress Susceptibility Index (SSI), with correlation coefficients of -0.67 and -0.83 for the spring and fall seasons, respectively. The SSI was also negatively but not significantly correlated with Yp (-0.51 and -0.45 for the spring and fall seasons, respectively). This suggests that SSI identifies genetic lines that are susceptible and low-yielding under drought conditions (Ys). The SSI was positively and significantly correlated with TOL (0.63 and 0.95) and negatively correlated with RDI (-0.97 and -0.99 for the spring and fall seasons, respectively). On the other hand, the RDI index was positively correlated with Ys, with correlation coefficients of 0.88 and 0.72 for the spring and fall seasons, respectively.

Table 6. Simple Linear Correlation of Drought Indices with Grain Yield for 25 Sorghum Genotypes in the Spring Season 2024

	YP	YS	MP	GMP	STI	TOL	SSI	RDI
YP	1.00							
YS	0.44	1.00						
MP	0.81	0.95	1.00					
GMP	0.87	0.93	0.93	1.00				
STI	0.79	0.91	0.95	0.98	1.00			
TOL	0.98	0.44 -	0.80	0.63	0.76	1.00		
SSI	0.51	0.67-	0.53-	0.44-	0.60-	0.63	1.00	
RDI	0.39	0.88	0.34	0.45	0.46	0.38-	0.97-	1.00

Table 7. Simple Linear Correlation of Drought Indices with Grain Yield for 25 Sorghum Genotypes in the Fall Season 2024

	YP	YS	MP	GMP	STI	TOL	SSI	RDI
YP	1.00							
YS	0.82	1.00						
MP	0.88	0.93	1.00					
GMP	0.91	0.80	0.90	1.00				
STI	0.89	0.73	0.87	0.99	1.00			
TOL	0.73	0.49-	0.28	0.04	0.11	1.00		
SSI	0.23-	0.83-	0.47-	0.33-	0.42-	0.95	1.00	
RDI	0.38-	0.72	0.38	0.41	0.53	0.91-	0.99-	1.00

*** 5% r = 0.23 ** 1% r = 0.19**

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) is a technique used for data reduction and summarization to better understand relationships, similarities, and differences among drought tolerance indices. PCA relies on a correlation matrix between drought tolerance indices. The main advantage of this analysis is the ability to classify the indices into different groups. An interesting interpretation of the biplot is that the cosine of the angle between two vectors (variables) approximates the correlation coefficient between them. The angle between the vectors reflects the correlation between the variables, and this provides a simple and clear representation of the relationships between the variables. Based on the above, the relationship between drought tolerance indices can be visually represented in a two-dimensional (PCA1 and PCA2) biplot to show the relationship between tolerance indices and genotypes. The first principal component, PCA1, explains 72.8% and 58.1% of the total variance for the fall and spring seasons, respectively. PCA1 is positively correlated with Ys, Yp, MP, STI, and GMP, and this component can be named the Yield and Drought Tolerance Component**.** Genotypes with high positive values for PCA1 are those with high yield potential under both Ys and Yp conditions. The second principal component, PCA2, explains 26.8% and 41.2% of the total variance for the fall and spring seasons, respectively. PCA2 is positively correlated with Ys and STI for the fall season and Ys and RDI for the spring season. This component could be named the Stress Tolerance Component**;** it differentiates genotypes that are tolerant to stress from those that are not. Thus, selecting genotypes with high values for both PCA1 and PCA2 would be suitable for both stress (Ys) and non-stress (Yp) conditions. In this regard, the genotypes G17, G13, G10, G7, and G25 are suitable for both stress and non-stress conditions in the fall season (Figure 1), and the genotypes G25, G22, G20, G19, G12, G7, G14, and G15 are suitable for both stress and non-stress conditions in the spring season (Figure 2). Genotypes with negative values for both PCA1 and PCA2 are unsuitable for both stress (Ys) and non-stress (Yp) conditions. These genotypes include G24, G22, G6, G5 for the fall season and G18, G17, G11, G6, and G5 for the spring season (Figures 1 and 2). Finally, genotypes with positive values for PCA1 and negative values for PCA2 are suitable under stress conditions (Ys) but not under non-stress conditions. These genotypes include G21, G19, G15, G14, G11, G9, and G23 in the fall season and G21, G16, G13, G8, G14, and G24 in the spring season, showing the highest yield potential under drought stress conditions (Figures 1 and 2).

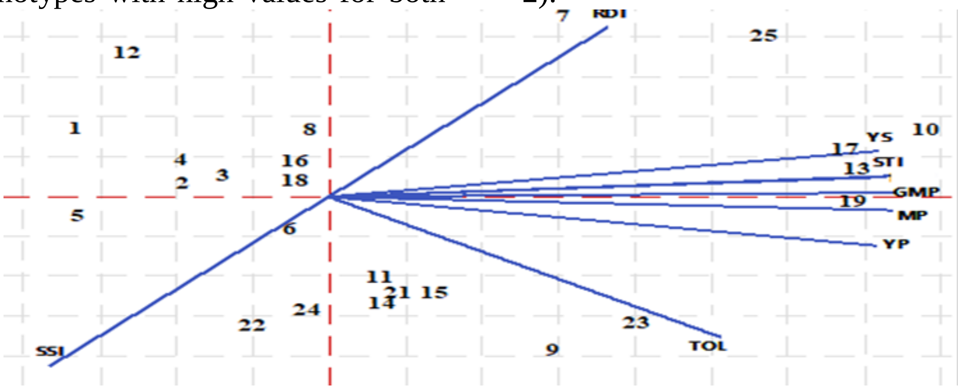

Figure 1. Results of Principal Component Analysis for the genetic composition classification of the spring season 2024

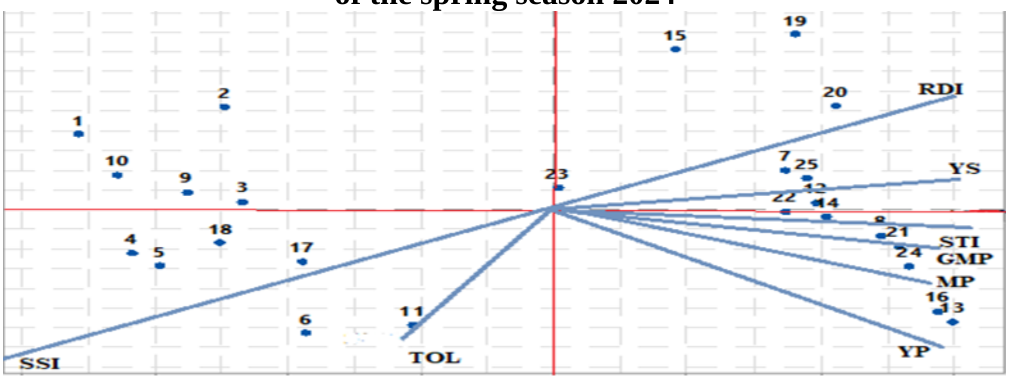

Figure 2. Results of Principal Component Analysis for the genetic composition classification of the fall season 2024

Rank Analysis: The results obtained from the drought indices used produced sometimes contradictory outcomes in determining the ranks of genetic compositions based on their drought tolerance (Tables 5 and 6). Therefore, it became essential to develop an index that considers the results from all these indices, taking into account the mean and standard deviation of the ranks for each genetic composition across all the drought indices used. This index was named the Ranksum (RS) (6). Based on its results, the genetic compositions G8, G11, and G2 were classified as drought-tolerant, while the genetic compositions G15, G16, and G12 were classified as drought-sensitive for both seasons (Tables 5 and 6). This method has been used by several researchers for various crops (1, 6, 16,21).

Cluster Analysis: The purpose of cluster analysis is to perform statistical operations that form homogeneous groups within each cluster and distinctively between different clusters to study genetic diversity or variation, and to group similar genetic compositions based on the results from applying drought indices. The distance between one group and other groups indicates the degree of relatedness. Groups that are closer to each other are placed in branches that are nearer together. Although this method is an approximation, it is a simple approach for studying relationships and evolution. The cluster analysis of the studied genetic compositions reveals a dendrogram of genetic relationships, relying on Yp, Ys, and other drought indices used for sorghum genetic compositions. The figure shows the genetic compositions on the x-axis, and the similarity ratio in Euclidean distance (sum of squared differences for each variable) between genetic compositions. The analysis identified five groups of genetic compositions for both the spring and fall seasons. For the spring season, the first group (Group 1) contains the genetic composition G24, which belongs to group D according to Fernandez's classification (1992). This composition exhibits low productivity in both Yp and Ys. The second group includes the genetic compositions G10, G13, G17, and G10, which belong to group B and show good productivity under non-stress conditions (Yp only). The third group includes the genetic compositions G7 and G25, which belong to group A, showing high productivity in both Yp and Ys. The fourth group includes the genetic compositions G14, G15, G20, G21, G23, G9, and G11, which belong to group C and show good productivity under drought conditions (Ys only). The fifth group includes the remaining genetic compositions that do not clearly belong to any of the four previous groups (A-D) (Figure 3). For the fall season, the first group (Group 1) contains the genetic compositions G18 and G17, which show low productivity in both Yp and Ys. The second group includes the genetic compositions G9, G2, and G10, which belong to group B and show good productivity under non-stress conditions (Yp only). The third group includes the genetic compositions G20, G19, and G15, which belong to group A, showing high productivity in both Yp and Ys. The fourth group includes the genetic compositions G21, G16, G13, G12, G8, and G24, which belong to group C and show good productivity under drought conditions (Ys only). The fifth group includes the remaining genetic compositions that do not clearly belong to any of the four previous groups (A-D) (Figure 4).

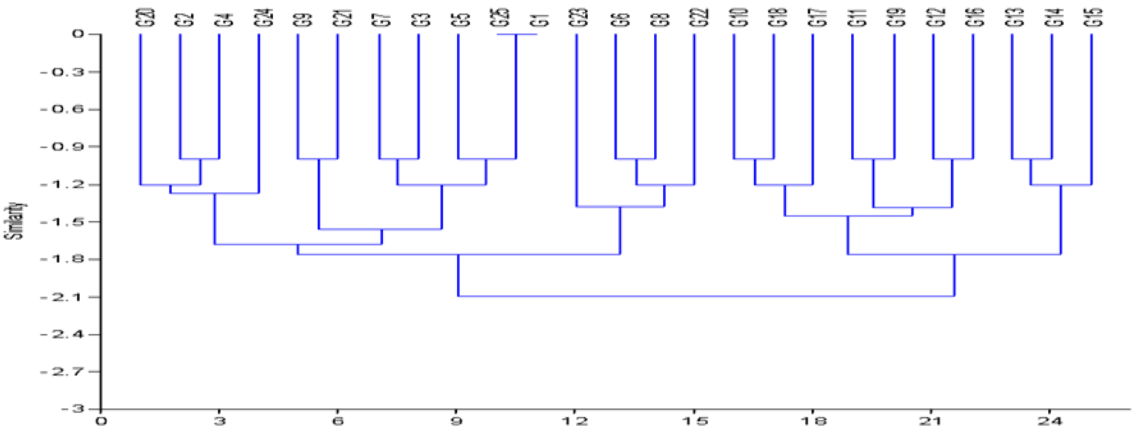

Figure 3. Results of cluster analysis for the classification of strains for the spring season 2024

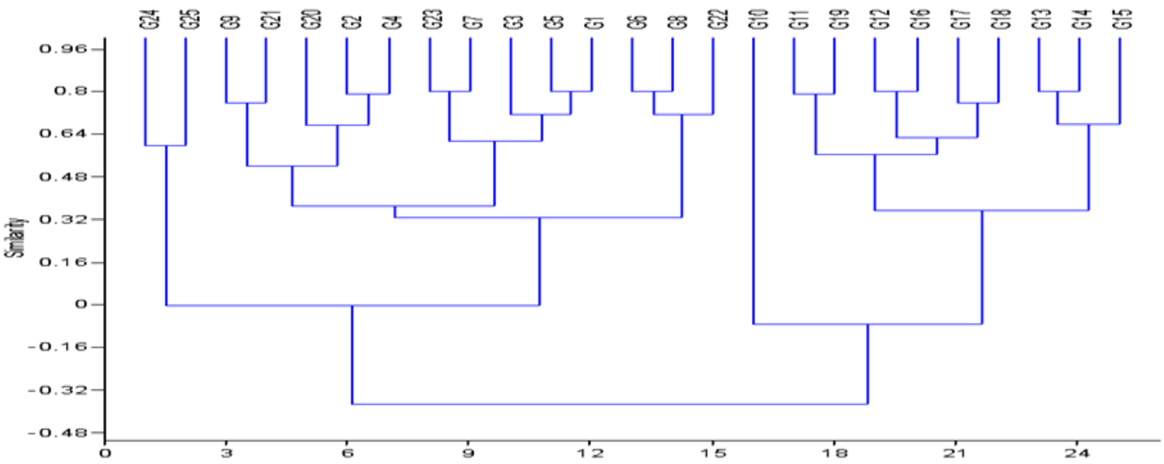

Figure 4. Results of cluster analysis for the classification of strains for the season fall 2024

CONCLUSION

Based on the correlation coefficient, principal component analysis, biplot, cluster analysis, and rank analysis, the indices Mp, GMP, and STI are positively and significantly correlated with Yp and Ys. Therefore, these indices have a high capacity to identify genetic compositions with high productivity potential under both stress and non-stress conditions. Regarding the genetic compositions, G25 (ACSAD 68) , G22 (ACSAD 65), G20 (ACSAD 62), G19 (ACSAD 61), G12 (ACSAD 36), G7 (Giza 113) , G14 (ACSAD 51), and G15 (ACSAD 56), are suitable under both stress and non-stress conditions in the spring season. In the fall season, the genetic compositions G17 (ACSAD 58),, G13 (ACSAD 47),, G10 (Uruk), G7 (Giza 113), and G25 (ACSAD 68) are suitable under both stress and non-stress conditions. These genetic compositions exhibit drought tolerance and high productivity under both stressed and non-stressed environments (Figure 1).

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

DECLARATION OF FUND

The authors declare that they have not received a fund.

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