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Lint Yield Stability of Different Cotton (*Gossypium barbadense* L.) Genotypes Using GGE Biplot under Normal and Drought Irrigation Conditions

Yehia, W. M. B.[1] and E. F. El-Hashash[2*]

[1]Cotton Research Institute – Agriculture Research Center – Giza- Egypt.
[2]Department of Agronomy, Faculty of Agriculture, Al-Azhar University, Cairo, Egypt.

ABSTRACT

The GGE-biplot model is used in this study to evaluate the 24 genotypes (G), five environments (E), and GE interaction for lint cotton yield (kg ha^{-1}) and to identify high-yielding and stable cotton genotypes under normal irrigation (NI) and drought irrigation (DI) conditions at Sakha Agriculture Research Station, Kafr El-Sheikh Governorate, Egypt. The combined ANOVA revealed that the G, E, and GE interaction had a highly significant effect on lint cotton yield. The effects of E (36.18%) and GE interaction (59.45%) explained the majority of the variation in lint cotton yield under NI and DI conditions, respectively. The GE interaction in the GGE biplot has been partitioned among the PC1 and PC2, together accounting for 95.80% and 65.60% of the total G+GE variation under NI and DI conditions, respectively. Drought stress drastically reduced lint cotton yield across five environments compared with NI conditions. The GGE biplot stability and adaptability revealed that genotypes G20 and G5 were the most stable and productive across environments, unlike the genotypes G1 and G18 under NI and DI conditions, respectively. The GGE biplot performed well in the GE interaction study, and it provides a clear idea of genotype stability behavior in both irrigation conditions. According to the GGE biplot model, G5 can be recommended as the most biological stable genotype in terms of both stability and lint cotton productivity across drought stress environments and poor climatic conditions.

***Keywords**:* GE interaction, GGE biplot, Stability, *Gossypium barbadense* L.

INTRODUCTION

Cotton is the world most important natural textile fiber crop, as well as one of Egypt most important cash crops. In Egypt, cotton is commonly known as "white gold", due to its important role in industrial development (fiber and oil) and employment generation. In light of climate change, it is now more important than ever to explore the possibilities of drought-tolerant crops for all sorts of land crops (El-Hashash and Agwa, 2018). The concept of drought resistance is a complex phenomenon and controlled by multi-gene that manifests both drought tolerance (tissue tolerance, photosystem maintenance, and so on) and drought avoidance (deep root, leaf rolling, and so on) features (Solis *et al*., 2018).

Plant breeding programs' major target is to increase crop yield stability and consistency in many environments (locations and/or years). The yield performances of genotypes could differ significantly when they are assessed in a wide of different environments (Ebem *et al*., 2021). The association between the environment and the phenotypic expression of a genotype is commonly known as the genotype (G) x environment (E) interaction. GE interaction is a common phenomenon or routine occurrence in plant breeding programs (Kang, 1998), resulting from variations in the degree of differences among genotypes in different environments conditions or changes in the genotypes relative ranking (Ebdon and Gauch, 2002), from one environment to the next, or a difference in scale between environments, or a combination of the two (Mohammadi and Amri, 2008). The evaluation and understanding of the genotypes x environment interaction is one main step toward the development of improved crop genotypes (Sabri *et al.*, 2020). To estimate GE interaction effects, breeders test genotypes in a variety of environments (years and/or places) to find those with high and steady performance and superior adaptation (Yan *et al.*, 2000). The genotypes/varieties with insignificant GE interaction are considered to be stable (Ssemakula and Dixon, 2007). There are several statistical modeling tools by biometricians that can be used for evaluating and interpreting GE interaction, such as genotype (G) main effect plus genotype-by-environment (GE) interaction (GGE) biplot.

Yan *et al.* (2000) introduced the GGE biplot methodology, which is a sophisticated statistical model that addresses some of the AMMI model disadvantages. The GGE biplot has proven to be very effective, and it is a more comprehensive approach for analyzing GE interaction in different mega environments in plant breeding and quantitative genetics (Yan and Rajcan, 2002; Yan *et al.*, 2007). The GGE biplot combines two important sources of variation in mega environments (Genotype and G×E), thus the name GGE. Also, it is utilized for mega environment analysis ("Which- Won-Where" pattern), genotype assessment (ranking biplot), and environment evaluation (comparison biplot), hence the name GGE biplot, which provides discriminating power and environment representation (Yan and Tinker, 2006).

[*] **Corresponding author.**
E-mail address: dressamelhashash@yahoo.com
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In the mega-environment analysis and genotype evaluation, the GGE biplot is superior to the AMMI graph in several things, which are: genotype evaluation by mean vs. stability view, explains more G+GE, easier to visualize the which-won-where patterns (AMMI could be misleading), has the inner-product property of the biplot, effective in evaluating test environments by discriminating power vs. representativeness (which is not possible in AMMI analysis) and shows the relative performance of each genotype in each environment (Yan and Tinker, 2006). Furthermore, in terms of explaining the PC1 score, which represents the genotypic effect rather than the additive main effect, the GGE biplot is more logical and biological for practice than AMMI models (Yan *et al.,* 2000). Generally, the GGE biplot is always near the top AMMI analysis in the majority of circumstances, when compared to different AMMI family models (Ma *et al.,* 2004).

As a result, the goals of this investigation were to (1) evaluate the GE interaction, identify cotton genotypes with high yield and stable performance across five consecutive growing seasons under normal irrigation and drought irrigation conditions using GGE biplot model, and (2) select drought-tolerant genotypes of Egyptian cotton.

MATERIALS AND METHODS

Genetic Material and Field Procedure

The current study was conducted at Sakha Agriculture Research Station, Kafr El- Sheikh Governorate, Egypt. A total of 24 cotton genotypes belonging to *Gossypium barbadense* L. were chosen and listed in Table 1.

Table 1. A list of the 24 cotton genotypes tested for drought tolerance.

No.	Genotypes	Pedigree	Origin
G1	Giza 89	Giza 89 x 6022	Egypt
G2	Z101	Unknown	Unknown
G3	Giza 85	Giza 67 x CB58	Egypt
G4	Giza 75	Unknown	Egypt
G5	Giza 94	10229 x Giza 86	Egypt
G6	A106	Unknown	Unknown
G7	A101	Unknown	Unknown
G8	Z102	Unknown	Unknown
G9	Giza 89 x Giza 86	Unknown	Egypt
G10	Giza 45	Giza 28 x Giza 7	Egypt
G11	A108	Unknown	Unknown
G12	Giza 93	Giza 77 x S106	Egypt
G13	D101	Unknown	Unknown
G14	Giza 70	Giza 59A x Giza 51B	Egypt
G15	A105	Unknown	Unknown
G16	G102	Unknown	Unknown
G17	R101	Unknown	Unknown
G18	G101	Unknown	Unknown
G19	Giza 96	(Giza 84 x (Giza 70 x Giza 51B)) x S62	Egypt
G20	Giza 86	Giza 75 x Giza 81	Egypt
G21	Giza 95	(Giza 83 x (Giza 75 x 5844)) x Giza 80	Egypt
G22	S106	Unknown	Unknown
G23	S107	Unknown	Unknown
G24	S109	Unknown	Unknown

Healthy seeds of cotton genotypes were provided by the Cotton Research Institute, Agriculture Research Center, Giza, Egypt. These cotton genotypes were assessed in a Randomized Complete Block Design (RCBD) with three replications under normal irrigation (NI) and drought irrigation (DI) conditions separately during five successive growing seasons from 2016 to 2020. Each genotype was sown in the experimental plot, each plot included five rows with a four-meter-long row. The row and plant spacing's were maintained at 70 and 30 cm, respectively. Plot size kept was 13 m^2. For NI conditions, eight irrigations (4200 m^3 of water) -one at sowing and seven other irrigations with an interval of 15 days were applied at various crop growth stages. Under the DI conditions, the plot was irrigated five times (3150 m^3 of water) with one at the time of sowing and the other four irrigations were applied with an interval of 30 days. Each experiment employed a basin irrigation system with PE pipes and a volumetric counter. Even if the drought stress was severe, no supplemental irrigation was provided after drainage in the drought stress experiments. The crop was sown in a single day, and all of the prescribed cotton production agricultural methods in the area were followed as usual, with uniform field conditions to reduce environmental differences to the greatest extent possible. After removing the border effects, the plants in each plot from the three middle rows were harvested to determine lint cotton yield/plot, which was then converted to yield kg ha^{-1}.

Statistical analysis

The data of lint cotton yield (kg ha-1) for 24 cotton genotypes in five growing seasons were subjected to combined ANOVA utilizing software PBSTAT to determine the existence of variances among the 24 genotypes, five years (environments), and GE interaction. After determining the significance of the GE interaction, adaptation ability and phenotypic stability analyses for genotypes studied were performed graphically using the GGE-biplot model (Yan *et al.,* 2000) in both irrigation conditions.

RESULTS AND DISCUSSION

Results

Climatic data of the study area

Table 2 displays cultivated location climatic data such as monthly average temperature (ºC), average precipitation (mm), and relative humidity (%) from April to October over five growing seasons. The highest percentage of precipitation and relative humidity, and the lowest average temperature rates during the studied period were recorded in April at the 2017 and 2020 growing seasons. The amount and distribution of precipitation varied across the five growing seasons, resulting in contrasting growing conditions and, as a result, a range of yield potentialities under DI conditions.

Combined ANOVA

The data of combined ANOVA for each trial individually for lint cotton yield (kg ha^{-1}) is illustrated in Table 3. Combined ANOVA table showed that lint cotton yield was highly significantly affected by genotype (G), environment (E), and GE interaction in both irrigation conditions. After subtracting sums of squares (SS) of error and replication, the effects of E, G, and GE interaction explain 85.62% and 84.64% of the total SS under NI and DI conditions, respectively. The SS% of E and GE interaction were of greater magnitude than other sources of variation, explaining 36.18% and 59.45% the total SS under NI and DI conditions, respectively. Lint cotton yield showed moderate values of coefficient of variations (CV%) with values of 10.03% and 12.88 in both irrigation conditions, respectively.

Table 2. Monthly climate data from the experimental period (April to October) in the experimental location over a five-year period.

Climate	Years	Months							
		April	May	June	July	August	September	October	Mean
Temperature average	2016 (E1)	23.85	25.51	30.01	29.89	29.76	28.5	25.47	27.57
	2017 (E2)	20.22	28.92	30.86	30.24	28.1	23.69	27.12	27.02
	2018 (E3)	22.69	26.98	29.01	30.22	30.08	28.88	25.53	27.63
	2019 (E4)	19.86	26.52	29.27	30.29	30.48	28.12	26.08	27.23
	2020 (E5)	19.58	24.06	27.69	29.86	30.44	30.18	27.12	26.99
Average precipitation	2016 (E1)	0.07	0.00	0.00	0.00	0.00	0.00	0.48	0.08
	2017 (E2)	2.68	0.36	0.34	0.00	0.00	1.38	0.07	0.69
	2018 (E3)	0.07	0.00	0.00	0.1	0.00	0.00	0.15	0.05
	2019 (E4)	0.12	0.00	0.00	0.00	0.00	0.00	0.55	0.10
	2020 (E5)	3.43	0.00	0.00	0.00	0.00	0.00	0.07	0.50
Relative humidity	2016 (E1)	50.19	48.32	48.66	54.51	57.41	55.93	63.42	54.06
	2017 (E2)	59.74	50.23	53.55	55.35	57.56	63.00	60.19	57.09
	2018 (E3)	52.38	51.39	48.67	54.97	57.37	57.23	58.85	54.41
	2019 (E4)	56.79	44.73	52.85	52.9	55.16	58.00	62.09	54.64
	2020 (E5)	64.05	59.35	51.10	54.99	56.65	58.92	60.19	57.89

Source: Climate Change Information Center and Renewable Energy, Agriculture Research Center, Cairo, Egypt.

Table 3. Effects of genotypes, environments and their interaction on lint cotton yield using ANOVA of pooled data for 24 cotton genotypes across five years under normal irrigation (NI) and drought irrigation (DI) conditions.

S.O.V.	df	NI conditions			DI conditions		
		SS	MS	% Explained	SS	MS	% Explained
Environments(E)	4	188766462.9	47191615.73**	36.18	41845203.42	10461300.85**	11.55
Replication/E	10	6639525.17	663952.52*	1.27	2155512.13	215551.21^{ns}	0.60
Genotypes(G)	23	104077988.7	4525129.94**	19.95	49407858.3	2148167.75**	13.64
G x E	92	153850377.1	1672286.71**	29.49	215295032.1	2340163.39**	59.45
Error	230	68417760.87	297468.53	13.11	53447820.58	232381.83	14.76
Total	359	521752114.7	1453348.51		362151426.5	1008778.35	
CV%			10.03			12.88	

*** and **: Statistically significant differences at $P \leq 0.05$ and $P \leq 0.01$, respectively; ns: the non-significant difference ($P>0.05$).**

Genotypic mean performance across five years

As shown in Table 4, each year was treated as a separate environment. In both irrigation conditions, mean comparisons of lint yield revealed significant differences among investigated genotypes in each environment.NI conditions resulted in a significant increase in lint yield when compared to DI conditions over the five years studied. Under NI and DI conditions, the average environmental lint cotton yield of genotypes ranged from 2894.74 to 7406.93 kg ha^{-1}, and from 2029.00 to 5905.48 kg ha^{-1}, respectively.

Table 4. Mean performance and environmental index (EI) of lint cotton yield (kg ha^{-1}) of 24 genotypes investigated for five growing seasons and their combined under normal irrigation (NI) and drought irrigation (DI) conditions.

Years	NI conditions						DI conditions					
Genotypes	2016	2017	2018	2019	2020	Mean	2016	2017	2018	2019	2020	Mean
G1	4462.24	4549.07	4707.27	5753.62	6969.60	5288.36	2860.53	4123.50	2797.71	4813.63	5814.28	4081.93
G2	5667.05	5893.06	5528.74	4915.87	5728.18	5546.58	3431.99	3896.40	2534.04	3367.16	5905.48	3827.01
G3	5150.28	5956.13	6062.98	5989.75	6090.77	5849.98	3694.11	4685.53	3198.58	3545.22	4292.01	3883.09
G4	5155.81	5663.95	5645.95	4842.37	5224.61	5306.54	4761.52	4434.31	4230.52	4260.24	4558.75	4449.07
G5	6383.04	7134.40	7406.93	7272.00	6955.20	7030.31	4898.84	3636.73	3461.77	4600.03	4094.38	4138.35
G6	5044.77	5456.02	6291.50	4332.53	4552.27	5135.42	3382.35	3770.24	2783.16	4554.80	4690.66	3836.24
G7	6456.52	7123.39	6731.86	3664.62	4265.57	5648.39	4158.35	3441.13	2444.59	2444.18	4450.71	3387.79
G8	5128.31	5024.82	5293.22	4673.09	5185.44	5060.97	3891.17	4854.77	2197.36	2546.77	3323.01	3362.62
G9	6142.70	6436.18	6213.59	4386.77	4665.60	5568.97	3247.11	3493.10	3586.07	4103.05	3784.44	3642.75
G10	5684.86	5967.45	6092.70	3176.78	3627.22	4909.80	3306.30	2442.17	2720.26	4537.23	3325.78	3266.35
G11	5462.55	5642.46	5806.14	3939.83	4202.35	5010.67	2834.19	2426.43	2029.00	4334.03	4235.21	3171.77
G12	6511.14	7014.22	6840.54	2965.95	3766.03	5419.58	3584.75	3553.53	2175.36	3662.46	3604.81	3316.18
G13	6548.26	7288.46	7018.46	3475.57	3638.16	5593.78	3623.55	4051.77	3343.91	3737.59	2223.87	3396.14
G14	4695.21	4642.66	4473.19	4137.55	4176.00	4424.92	2905.63	3915.47	3005.15	4304.54	2234.21	3273.00
G15	7184.06	7142.40	7206.62	3900.20	4167.94	5920.24	2068.05	3634.10	2888.03	4706.47	2876.63	3234.66
G16	5733.64	5719.54	5669.87	4161.24	4448.74	5146.60	4912.30	3613.15	2782.66	4316.02	3430.74	3810.97
G17	6113.03	5938.67	6173.47	4375.05	4445.42	5409.13	5488.68	3460.79	2671.51	2582.18	3999.79	3640.59
G18	6412.32	7048.80	6984.00	3926.66	4173.26	5709.01	5466.14	4102.71	4093.10	2535.94	2293.30	3698.24
G19	6631.92	6609.60	6602.40	4849.78	5932.80	6125.30	3570.79	3771.70	4717.15	5883.52	2622.17	4113.07
G20	6648.19	6796.80	6941.87	5143.58	5874.62	6281.01	3461.04	3428.67	4236.96	5870.64	3126.25	4024.71
G21	5700.31	5626.75	5613.57	4216.34	4601.81	5151.76	4502.57	3411.12	2363.32	5120.63	4138.44	3907.22
G22	5660.19	5341.28	6217.51	3332.90	3713.76	4853.13	5725.70	3048.65	2397.89	4033.45	3988.38	3838.81
G23	6065.84	6135.00	5814.50	2894.74	3324.82	4846.98	4796.36	3731.74	4133.97	4312.50	3229.45	4040.80
G24	5572.35	5568.75	5779.85	4552.26	4908.96	5276.43	4592.79	3797.32	4709.54	5646.76	3554.45	4460.17
Mean	5842.27	6071.66	6129.86	4369.96	4776.63	5438.08	3965.20	3696.88	3145.90	4159.13	3741.55	3741.73
P-value	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	
LSD 0.05	840.11	393.16	455.51	1124.83	678.99	328.90	863.05	692.23	571.29	552.47	571.96	290.70
CV (%)	10.49	4.72	5.42	18.78	10.37	10.03	15.88	13.66	13.25	9.69	11.15	12.88
EI	-2.91	160.80	192.89	-264.08	-86.70		-10.12	37.61	-330.05	37.38	265.18	

According to the grand mean of lint yield for all evaluated genotypes, the most productive seasons were 2018 and 2019 with values of 6129.86 and 4159.13 (kg ha^{-1}) under NI and DI conditions, respectively. When using mean cotton yield as a first criterion for evaluating the genotypes, several genotypes had means exceeding the grand mean (5438.08 and 3741.73 kg ha^{-1}) in NI and DI conditions, respectively.

In general, the genotypes G5 in both irrigation conditions, the genotypes G19 and G20 in NI and the genotypes G24 and G4 in DI conditions gave better mean lint yields. While, the genotypes G14, G23 and G22, as well as the genotypes G11, G10 and G15 recorded the lowest lint yields under NI and DI conditions, respectively. As for the environmental index, the growing seasons 2018 and 2020 were recorded the highest values in NI (192.89) and DI (265.18) conditions, respectively. Lint cotton yield showed a high CV% in the growing seasons 2019 and 2016, with values of 18.78 and 15.88% under NI and DI conditions, respectively. In contrast to previous years, CV percent values in other growing seasons ranged from low (CV<10%) to moderate (10%<CV<15%) in both irrigation conditions.

GGE Biplot Analysis

1. Which-won-where pattern

The GE interaction is partitioned into two components (PC1 and PC2) by GGE biplot. The GGE biplot of PC1 contributed 56.30% and 36.00%, the PC2 explained 39.50% and 29.60%, and collectively they explained 95.80% and 65.60% of the total G+GE variation under NI and DI conditions, respectively (Fig. 1). The polygon view of the GGE biplot pattern of cotton yield was constructed to show which genotypes with the best performance best in which environment and groups of environments (Yan *et al.*, 2000), as well as to demonstrate the presence of crossover GE interaction, mega-environment differentiation, and specific adaptation (Yan and Tinker, 2006). Seven (G1, G5, G12, G13, G14, G15 and G23) and eight (G1. G2, G7, G15, G17, G18, G19 and G20) genotypes are located away from the biplot origin in all directions and which formed the polygon vertices during NI and DI conditions, respectively (Fig. 1). Whilst all other genotypes are encompassed within the polygon. A line perpendicular to each polygon side was drawn starting from the biplot origin. The biplot is divided into sectors by these lines. The rays are perpendicular lines to the sides of the polygon or their expansion (Yan, 2002). Thus, the five environments are divided into different apparent groups. The genotype at the vertices of each sector is the nominal highest yielder for the environments or mega-environments that fell into it. Accordingly, G5 produced maximum cotton yielding in E3, E4 and E5 while genotype G15 perform best in other environments under NI conditions. In the case of DI conditions, G2 was the highest cotton yielder in E5 whilst G19 was the highest cotton yielder in E3 and E4. The genotypes G24, G22 and G23 in NI conditions and the genotypes G10, G11 and G15 in DI conditions were the poorest across the environments, due to no environment falling into the sectors of these genotypes.

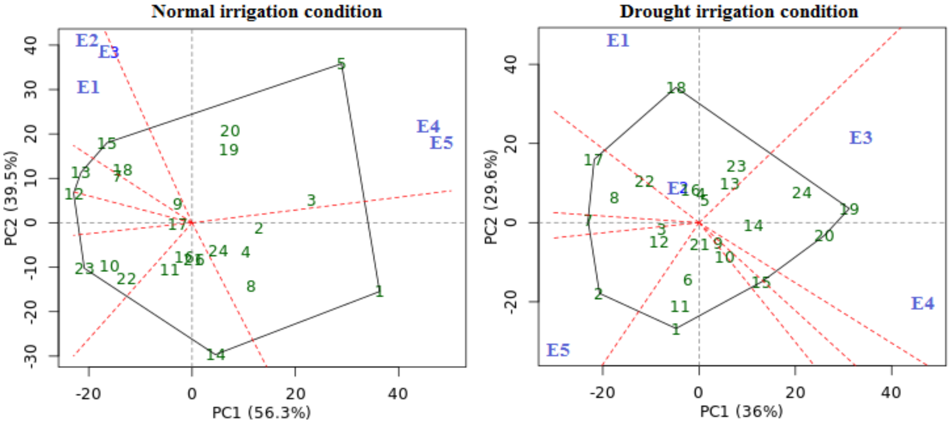

Fig. 1. GGE biplot polygon of "which-won-where" for lint cotton yield with 24 cotton genotypes (green color) and five environments (blue color) under normal irrigation (NI) and drought irrigation (DI) conditions. The genotypes and environment key names can be found in Tables 1 and 2, respectively.

2. Mean vs. stability analysis

The average environment coordination (AEC) method based on genotype-focused singular value partitioning (SVP) was utilized to assess genotype yield stability using average PCAs in all environments. If SVP = 1, the AEC line with a single arrow passes through the biplot's origin (Yan, 2002), the arrow points to a higher mean yield. The mean of PC1 and PC2 of the environmental scores is defined, as a report by Yan and Rajcan (2002). The 'Mean vs. stability' view is frequently referred to as AEC with SVP = 1 which helps to simplify the genotype assessment based on the mean performance and stability across environments within a mega-environment (Fig. 2). The GGE biplot was created by plotting the PC1 and PC2 produced from subjecting data of environment-centered yield to singular value decomposition (Yan *et al.*, 2000). The genotypes are grouped according to their average cotton yielding, as indicated by the arrow sign on the AEC. The genotypes with above-average means were from G5 to G2 and from G19 to G9, while those with below-average means were from G12 to G14 and from G10 to G2 in NI and DI conditions, respectively. Genotype G5, G20 and G19 produced higher cotton yield in E4 and E5 in NI conditions, while the low yield was recorded by G23 in the same environments. As for during DI conditions, G24, G19 and G20 had the highest mean cotton yield, whereas G11 had the least mean cotton yield in E3 and E4. The highest cotton yield was recorded for genotype G1 and G2 in E5 under NI and DI conditions, respectively. G11, G16, G17, G19, G20 and G21 in NI conditions and G12, G2, G3, G5, G13 and

G21 in DI conditions were the most stable genotypes, as they were located almost on the AEC abscissa and had a near-zero projection onto the AEC ordinate. According to Yan *et al.* (2007), this shows that these genotypes ranking was highly consistent across environments. In addition to good cotton yield, genotype stability is more important, in terms of Yan (2001) established an "ideal" genotype based on average performance as well as stability. Thus, the genotypes G20 and G19 in NI conditions and the genotypes G5 and G4 in DI conditions are more stable with better mean cotton yield other than the other genotypes. Reciprocally, the genotypes G1 and G18 are more variable and highly unstable with below and above-average mean performance in both conditions, respectively.

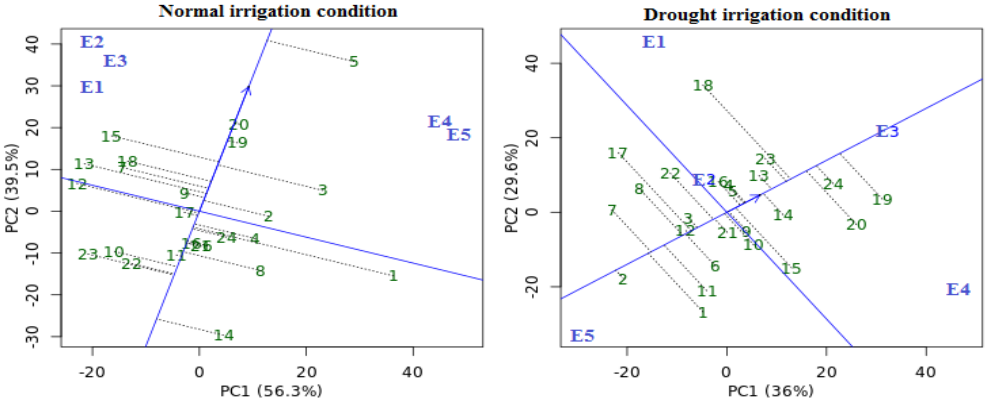

Fig. 2. GGE biplot of mean vs. stability for lint cotton yield with 24 cotton genotypes (green color) and five environments (blue color) under normal irrigation (NI) and drought irrigation (DI) conditions. The genotypes and environment key names can be found in Tables 1 and 2, respectively.

3.Discriminitiveness vs. representativeness pattern

For a successful breeding approach in the selection of superior genotypes for a mega-environment, determining the best-suited (ideal) test environment is critical by the test-environment evaluation (Yan *et al.*, 2007). The idealness of the tested environments is defined by two characteristics: a) discriminating ability (the ability of an environment to differentiate genotype in terms of main genotype effects), which has a high PC1 score, and b) representativeness (the ability of an environment to represent all other evaluated environments), which has a zero score for PC2. As a report by Yan et *al.* (2007), due to having the smallest angles with AEC, the test environments E2 and E3 in both irrigation conditions are more representative of other test environments (Fig. 3). The test environments E2 and E3 had longer vectors and smaller angles with AEC under NI and DI conditions, respectively, indicating that these environments are idyllic and have the greatest ability to discriminate genotypes, thus favoring the selection of superior genotypes. Yan *et al.* (2000) and Yan and Rajcan (2002) reported that the most genotypes desirable is the one closest to the graph of the ideal environment. Thus, the genotype G5 is the most productive and stable in both irrigation conditions. While the test environment E5 had a larger angle with AEC, indicating that it was the least discriminating and representative in both irrigation conditions. Non-discriminating test environments provide minimal information about genotypes and must not be used as test environments (Yan and Tinker, 2006).

According to Yan and Kang (2002), the acute angles (strong positive correlation) were observed among E1, E2 and E3 and between E4 and E5 in NI conditions, while E3 had positively correlated with E2, E4 (moderate) and E1 (slight) in DI conditions (Fig. 3). As a report by Yan and Tinker (2006), the length vectors and the cosine of the angle between the two environments determine the similarity (covariance) of them. Therefore, the environments in NI conditions were divided into two distinct groups by the ray's lines: the first group included E4 and E5, and the second group comprised the other environments. As for DI conditions, there are three groups: the first group consists of E3 and E4, the second group is composed of E1 and E2, while E5 belongs to the third group.

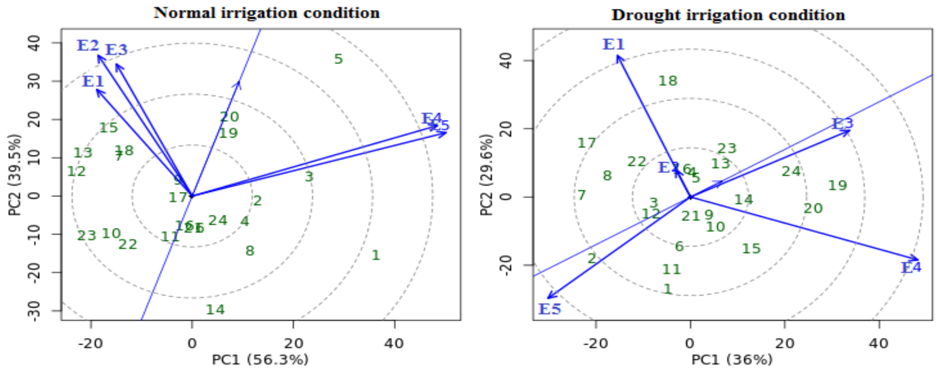

Fig. 3. GGE biplot of discrimitiveness vs. representativeness for lint cotton yield with 24 cotton genotypes (green color) and five environments (blue color) under normal irrigation (NI) and drought irrigation (DI) conditions. The genotypes and environment key names can be found in Tables 1 and 2, respectively.

Discussion

Results of combined ANOVA showed significant differences among genotypes (G), environments (E), and their interaction for lint cotton yield (kg ha^{-1}) in both irrigation conditions. These results indicate the existence of high diversity among genotypes and confirm that the testing environments were different, which enables us to select genotypes under both irrigation conditions, especially drought stress. Also, our results indicated the variability and inconsistency in the lint cotton yield in responses of 24 genotypes over the five environments in both irrigation conditions, as determined by these models. So, assessing the stability of lint cotton yield for these different genotypes, especially under DI conditions, would be perfect for selecting a cotton genotype with higher lint cotton yield and better stability. Interestingly, the above results are similar to findings that were observed in cotton earlier studies such as Mudada *et al.* (2017); Riaz *et al.* (2019); Teodoro *et al.* (2019); Lingaiah *et al.* (2020); Kumbhalkar *et al.* (2021) and Vavdiya *et al.* (2021).

According to Moll *et al*. (1978), a significant GE interaction can be partitioned into components representing genotypic variations in responsiveness to environmental variation and differences in correlations between pairs of genotypes under environments evaluated. After partitioning GE interaction by GGE biplot, the PC1 contribution in the GE interaction was greater than the PC2 in both irrigation conditions, suggesting that the GGE biplot effectively partitioned the variability in lint yield. A similar trend has been reported in cotton under DI conditions by Riaz *et al.* (2019). According to *Yan et al. (2007),* the GGE biplot always explains more variation in GE interaction than other models.

Lint cotton productivity was found to be significantly lower in DI conditions compared to NI conditions, ranging from 16.50% to 22.37% across five environments, indicating genetic variability in 24 cotton genotypes for drought tolerance. Bakhsh *et al.* (2019), Li *et al.* (2020) and Mahmood *et al.* (2021) both reported similar findings. Opposite for the genotypes G14 and G11, the genotypes G5 and G24 had the maximum lint cotton yield across all environments under NI and DI conditions, respectively. During NI conditions, these genotypes gave the best lint cotton yielding, but some genotypes also performed well under DI stress, indicating their incompatible relative performance and high susceptibility to environmental changes (El-Hashash and Agwa, 2018). Thillainathan and Fernandez (2002) stated that yield stability may be due to consistent performances across different environments (locations and/or years). The GE interaction effect was of the crossover type, as evidenced by the differential yield ranking of genotypes across environments (Yan and Hunt, 2001). The values of CV% indicate that the genotypes had exploitable genetic variability during lint cotton yield selection. Similar to Manan *et al.* (2021), the low CV% proved the accuracy of the cotton experiment under NI and DI conditions. The CV% values in cotton were determined to be less than 10% by Yehia and El-Hashash (2021) and El-Hashash and Yehia (2021), but they were larger than 10% by Li *et al*. (2020).

Breeders may be able to generate more stable genotypes if they have a better grasp of the relative contributions of genotypes, environments, and their interactions as sources of variation (Basford and Cooper, 1998). The fact that there was a significant GE interaction for yield shows that some genotypes were stable while others were unstable (El-Hashash and Agwa, 2018). Only qualitative or crossover interactions are relevant in agriculture, according to Baker (1988) and Crossa (1990), and suitable statistical analysis is necessary to quantify them. Therefore, there is a need for assessing the stability of yield for each of the 24 cotton genotypes in order to identify genotypes with superior cotton yield under DI conditions by applying the GGE biplot model.

Most cotton genotypes were high-yielding and stable. The GGE biplot identified G20 and G5 as stable genotypes with the highest mean lint cotton yield across environments under NI and DI conditions, respectively. Whilst, G1 and G18 were the unstable genotypes under NI and DI conditions, respectively. The biplot graphical interpretations are the most trustworthy for representing standards in applied data (Machado *et al.,* 2019). In the investigation of GE interaction, the GGE biplot was effective and provide favorable findings, where it showed a clear distinction among evaluated genotypes in terms of yields and stability across NI and DI conditions.

The ideal environment is only an estimate and is used to guide site selection in the multi-environment trials (Tena *et al.,* 2019). According to the GGE biplot, test environments E2 and E3 for lint cotton yield are regarded as the ideal environments under NI and DI conditions, respectively. These environments tend to discriminate the genotypes in the same direction (Alizadeh *et al.,* 2017), and they are used as an excellent index for selecting genotypes with the best average performance and adaptability (Murphy *et al.,* 2009). Oppositely, test environment E5 was found to be the worst environment for genotype selection in both irrigation conditions. Because of its high discriminating power and representativeness, the ideal test environment would be appropriate for choosing superior genotypes. Based on the distances between their markers and the marker of the ideal test environment, the GGE biplot can visually rate test environments for their utility in identifying superior genotypes (Yan *et al.,* 2007). Because the mean yield is more reproducible, the GGE biplot is more repeatable when calculated within mega-environments (Pour-Aboughadareh *et al.,* 2022). In cotton, the GGE biplot is a simple approach to assess the effect of genotype on the environment, and it gives useful information about the genotypes and environments under study (Kamali *et al.,* 2015; Sadabadi *et al.,* 2018). Finally, the GGE biplot models determined that genotype G5 was the most biologically stable with the high lint cotton yield and is recommended for use in Egypt under drought stress and poor climatic conditions.

CONCLUSION

The results of combined ANOVA reflect the divergent climatic conditions of five environments, resulting in a high level of genetic variability among 24 genotypes for lint cotton yield in both irrigation conditions. GGE biplot performed well in the study of the GE interaction, and provide a clear idea of genotype stability behavior in both irrigation conditions. According to the GGE biplot model, G5 can be recommended as the most biological stable genotype with regard to both stability and cotton yield across the drought stress environments and poor climatic conditions, therefore, this genotype must be released in the same regions in Egypt.

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ثبات محصول الشعر لتراكيب وراثية مختلفة من القطن باستخدام GGE biplot تحت ظروف الري العادي والجفاف

وليد محمد يحى[١] و عصام فتحى الحشاش[٢]

[١]قسم بحوث تربية القطن – معهد بحوث القطن – مركزالبحوث الزراعية – الجيزة – مصر

[٢]قسم المحاصيل – كلية الزراعة – جامعة الأزهر – القاهرة – مصر

تم استخدام نموذج GGE-biplot في هذه الدراسة لتقييم ٢٤ تركيب وراثي (G) وخمس بيئات (E) والتفاعل GE لمحصول القطن الشعر (كجم هكتار$^{-١}$) ولتحديد التراكيب الوراثية عالية المحصول والمستقرة تحت ظروف الري العادي والجفاف فى محطة البحوث الزراعية في سخا ، محافظة كفر الشيخ ، مصر. أشارت نتائج تحليل التباين التجميعى أن التراكيب الوراثية والبيئات والتفاعل بينهما كان له تأثير عالي المعنوية على محصول القطن الشعر. وقد فسرت تأثيرات البيئة (٣٦,١٨%) وتفاعل GE (٥٩,٤٥%) غالبية التباين في محصول القطن الشعر تحت ظروف الري العادي والجفاف، على التوالي. تم تقسيم تفاعل GE في GGE biplot بين المكونين PC1 و PC2 ، حيث يمثلان معًا ٩٥,٨٠٪ و ٦٥,٦٠٪ من إجمالي تباين G + GE في ظل ظروف الري العادي والجفاف، على التوالي. أدى الإجهاد الناتج عن الجفاف إلى انخفاض كبير في محصول القطن الشعر عبر الخمس سنوات نمو (البيئات) مقارنة بظروف الري العادي. كشفت نتائج الثبات والقدرة على التكيف لنموذج GGE biplot أن التراكيب الوراثية G20 و G5 كانت الأكثر استقرارًا وإنتاجية عبر البيئات ، على عكس التراكيب الوراثية G1 و G18 تحت ظروف الري العادي والجفاف، على التوالي. كان أداء تحليل GGE biplot جيدًا في دراسة تفاعل GE ، ويقدم فكرة واضحة عن سلوك استقرار التركيب الوراثي في كلا ظروف الري. وفقًا لنموذج GGE biplot ، يمكن التوصية بـالتركيب الوراثي G5 باعتباره التركيب الوراثي الأكثر استقرارًا من حيث الثبات الوراثي ومحصول القطن الشعر عبر بيئات الإجهاد التي تعاني من الجفاف والظروف المناخية السيئة.

الكلمات الدالة: تفاعل GE - GGE biplot - الثبات الوراثى – القطن (*Gossypium barbadense*, L.).