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Application of multivariate analysis to study genotype × environment interaction in sesame (*Sesamum indicum*) under stress conditions

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ABSTRACT

The present research aimed to study seed yield stability of 12 sesame (*Sesamum indicum* L.) genotypes evaluated across six environments (two growing years × three irrigation intervals). Data on seed yield were subjected to additive main effects and multiplicative interaction (AMMI) and genotype main effect and genotype × environment interaction (GGE) analyses using GenStat software. Results showed that environments main effect explained 73.9% of the total variation in seed yield compared with genotypes (12.3%) and genotypes × environment interactions (GEI) (10.9%). IPCAs showed significant effects and accounted for a total of 65.9% of GEI. IPCA1 had higher significant contribution to GEI (44.0%) than IPCA2 (21.9%). Based on AMMI stability value (ASV), genotypes 2, 3 followed by genotypes 1 and 11 were identified as the most stable and high yielding genotypes across tested environments. Furthermore, Environment 5, which is close to the biplot origin, is expected to be candidate environment for stable and repeatable genotype testing. Using GGE biplot model, considered G1, G7, G3 and G2 to be the most stable genotypes as they had the shortest vectors, moreover the most yielding genotypes were G7 and G2 as they were the most distance from the right side of the biplot and their yield surpassed the environmental mean. Introduced breeding lines are effective genetic source than local cultivated cultivars for high seed yield, such genotypes would be potential parental lines in sesame breeding programs.

Key words: Additive main effects and multiplicative interaction, Drought, Genotype × environment biplot (GGE), Sesame, *Sesamum indicum*, Stability

High temperature and drought are among major environmental stresses with significant impact on field crops growth and productivity. The decrease in annual precipitation that is predicted for Northern African countries in the 21st century will exacerbate expected rising temperatures effects, particularly in semiarid and arid regions that rely on irrigation for crop growth (Radhouane 2013).

With increasing world's population, the situation is getting serious and the ambiguity of weather patterns poses a challenge to plant breeders trying to develop adaptable crop varieties. Therefore, crop breeders perform multi-environment trials to evaluate new improved genotypes across test environments before a specific genotype is released for production (Karimizadeh *et al.* 2013), select and identify favorable genotypes based on both mean yield and performance stability (Gauch 2006, Yan and Kang 2003).

Multiplicative interactions (AMMI) and genotype plus GE interaction biplot (GGE) analysis have been developed and widely accepted by plant breeders and other researchers to investigate multi-environmental studies (Yan *et al.* 2000, It *et al.* 2016). Multi-environmental trials data analysis using AMMI partitions the GEI matrix into individual genotypic and environmental scores. AMMI Stability Value (ASV) was used to rank genotypes through the AMMI model, where significant correlation was recorded between ASV and other the stability measures (Purchase *et al.* 2000). Thus, ASV was considered to be the most appropriate method of describing stability of genotypes (Naroui *et al.* 2013).

GGE biplot has been applied to study GE interaction and yield stability analysis of different crops. It is useful method to identify high-yielding and stable cultivars and discriminating and representative test environments (Yan *et al.* 2000, Karimizadeh *et al.* 2013).

Several studies were extensively carried out on GEI by different researchers on various crops such as lentil and pea (Ito *et al.* 2016), sesame (Tadesse and Abay 2011, Abate and Mekbib 2015), soybean (Atnaf *et al.* 2013) and Sunflower (Ghafoor *et al.* 2005). They recorded highly significant mean squares for genotypes, environments and GEI, indicating the existence of a wide range of variation between the genotypes and between the seasons, therefore changing of genotypes performance over seasons.

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Sesame is one of the most important edible oilseed crops in Egypt. Seeds contain all essential amino and fatty acids and 44 to 60% oil. Total cultivated area and seed production of sesame was 14.173 ha and 198.356 ton in 2013, respectively. Egypt is considered one of the countries suffering from water scarcity as the total amount of water /capita/year is less than 1000 m^3. Thus, it is important to devote great efforts to the fundamental issue of increasing crops production while reducing their water consumption especially on the new reclaimed sandy soils (Abd El-Lattief 2015).

The present study was designed to measure the stability performance of sesame genotypes under six environments using AMMI and GGE biplot methods in order to identify the best performing and stable genotypes for specific environments.

MATERIALS AND METHODS

The genetic materials used in the present study comprising twelve sesame genotypes including in addition to one introduced variety (G10), eight local promising lines and hybrids (G1-G4,G7-G9 and G11), and three cultivated varieties (G5, G6 and G12). All genotypes were provided by Oil Crops Research Institute, Agricultural Research Center, Giza, Egypt. No previous studies on the responses of the tested materials to water stress have been conducted.

Two field trials were carried out at the experimental farm of Agricultural Research Station, Ismailia, Egypt, during the growing seasons 2012 and 2013. Mean day, night and relative humidity during the crop life cycle across two seasons were; 33.6 °C, 21.0 °C and 56.0%, respectively. No precipitation during the execution of field trials was received. The soil texture is sandy (90% sand, 3.8% silt and 6.2% clay), low in available N and organic matter (0.02% and 0.24%, respectively) and neutral pH (7.45). The genotypes were grown under three surface irrigation intervals (6, 9 and 12 days).

Water Consumption Use (WCU) assigned for each irrigation interval was calculated using the equation outlined by Israelsen and Hansen (1962). Total amount of applied irrigation water under 6, 9 and 12 days, averaged across genotypes and years was, 7368.2, 4880.0 and 3270.4 m^3/ha, respectively. One month after sowing, irrigation schedules were applied.

Split-plot arrangement in three replications was used, where irrigation intervals were assigned to main plots, and sesame genotypes were distributed in sub-plots. Each sub-plot consisted of 5 rows, 3 m in length and 0.60 m within rows. Sowing took place on May 17th and 19th in the first and second year, respectively. Calcium superphosphate (15.5% P_2O_5) and potassium sulphate (48% K_2O) were added during soil preparation. Nitrogen in the form of ammonium nitrate (33%) was manually added at three portions, sowing, after thinning and at flowering stages.

Seed yield was subjected to combined analysis of variance to determine the main effects of environment (E), genotype (G), and their interactions. The six environments arranged from Env1 to Env6, where Env1-Env3 refers to 6, 9 and 12 days irrigation intervals treatments in 2012 season, and Env4-Env6 refers to the same irrigation intervals in 2013 season. To evaluate the genotype × interaction effects, data were subjected to stability analysis following the AMMI model (Zobel *et al.* 1988).

AMMI Stability Values were calculated for each genotype to rank them in terms of stability according to the relative contribution of IPCA1 and IPCA2 to the interaction SS (Purchase *et al.* 2000) as follows:

$$ASV_1 = \sqrt{[SS_{IPCA1}/SS_{IPCA2}(IPCA1_{SCORE})]^2 + (IPCA2_{SCORE})^2}$$

where SS_{IPCA1}/SS_{IPCA2} is the weight given to the IPCA1 value by dividing the IPCA1 SS by the IPCA2 SS; and the IPCA1 and IPCA2 scores are the genotypic scores in the AMMI model.

The GGE biplot method (Yan *et al.* 2000) was also used to graphically identify the genotypic stability based on "which-won-where" pattern; ranking of genotypes on the basis of yield and stability. All statistical analyses were performed using GENSTAT software version 17.

RESULTS AND DISCUSSION

Combined analysis of variance

Combined analysis of variance for seed yield over six environments showed significant effect of environments, genotypes and their interactions (Table 1) indicating the differential responses of genotypes to irrigation regimes in both years. Sum squares due to environments explained 73.9% of the total variation, while genotypes and GE interactions constituted 12.3 and 10.9% of the total sum of squares. The large sum square for environment reveals the diversity of the tested environments that caused the most variation in sesame yield. Similar result was reported for grain yield of 36 wheat genotypes evaluated under control and drought stress, where environment and GEI contributed 51% and 14.9% of the total variation, respectively (Naroui Rad *et al.* 2013). In another study to analyze GEI in wheat

Table 1 Additive main effect and multiplicative interaction analysis of variance for seed yield of sesame genotypes evaluated in 2011 and 2012 seasons

SOV	Df	Sum squares	Mean squares	% Total SS	% GE
Treatments	71	8819801	124223*	97.1	
Genotypes (G)	11	1112856	101169*	12.3	
Environments (E)	5	6712607	1342521*	73.9	
Blocks	12	15777	1315		
G × E	55	994338	18079	10.9	
IPCA1	15	437724	29182*		44.0
IPCA2	13	218160	16782*		21.9
Residuals	27	338454	12535		
Error	132	243663	1846		
Total	215	9079241	42229		

substitution lines under normal and water stress conditions, environment, genotype and their interactions recorded 64%, 6.5% and 11% of the total sum of squares (Farshadfar *et al.* 2013). In contrast, variation due to genotypes explained the maximum contribution to sesame oil yield (47.1%) followed by environment (28.5%) and GEI (24.5%) (Abate and Mekbib 2015).

AMMI analysis

The presence of significant GEI confirmed the diverse responses of genotypes among environments, therefore GEI analysis through AMMI analysis (Table 1) is needed. The present AMMI analysis demonstrated the presence of significant G × E interactions, and this has been partitioned among the first and second Interaction Principal Components Axes (IPCAs). Both components showed significant effects and accounted for a total of 65.9% of GEI. IPCA1 had higher significant contribution to GEI (44.0%) than IPCA2 (21.9%). This suggested that, the other interaction principle components were not effective predictors in explaining observed GEI. Using the first two IPCAs to predict AMMI model accuracy was confirmed by many investigators (Gauch and Zobel 1996).

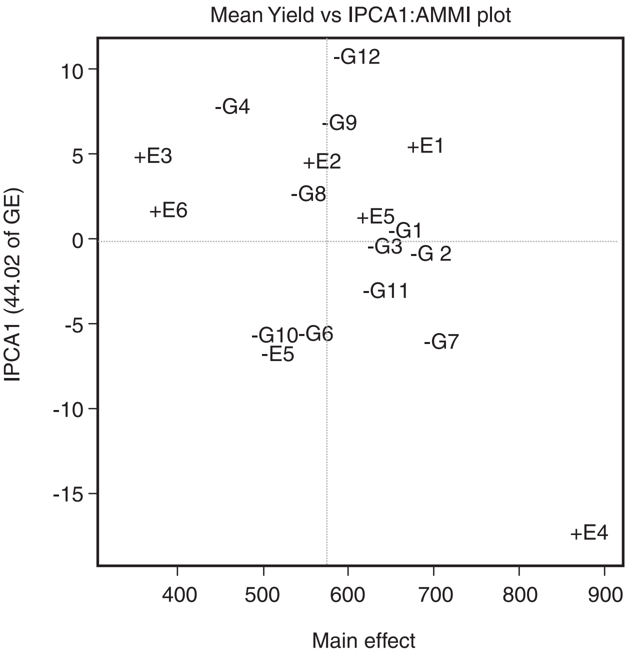

Fig 1 Additive main effect and multiplicative interaction biplot showing yield vs. PC1 of sesame genotypes and environments

Means, IPCA1 and IPCA2 scores and (ASV) for seed yield of 12 sesame genotypes are shown in Table 2. Mean seed yield ranged from 358.50 kg/ha at Env3 to 869.64 kg/ha at Env4, indicating that irrigation every 12 days resulted in nearly 58.7% seed yield reduction. Genotype 1 ranked the second and the first highest seed yielder under Env 1 and 3, respectively, while genotypes 7 and 12 had the highest seed yield at Env3. In the same context, genotype 7 recorded the highest mean seed yield under normal and medium irrigation conditions (Env1, Env2 and Env4), and was the highest above the grand mean value of genotypes. Generally, second season treatments were better for sesame yield production than the first. Genotype 4 produced the lowest yield over the tested environments and was far below the grand mean. According to ASV values, genotypes numbers 2 and 3 had the lowest values and considered the most stable genotypes, while genotype number 12 had the highest ASV values and considered the least stable genotype. This result is confirmed by the study

Table 2 Mean seed yield (kg/ha), IPCA1, IPCA2 scores and ASV of the 12 genotypes tested across six environments

Genotypes	Env1	Env2	Env3	Env4	Env5	Env6	Mean	IPCA1	IPCA2	ASV
M2A5 (G1)	651.43	582.55	415.24	899.69	779.69	486.98	635.93	0.200	-7.204	7.216
H102F21-2 (G2)	786.98	691.74	384.12	977.14	754.76	427.62	670.39	-0.817	-2.861	3.398
$H_{111}F_7$ (G3)	698.74	613.33	367.93	909.52	719.69	434.76	623.99	-0.192	-3.874	3.893
M_2A_7 (G4)	591.67	411.90	341.26	610.79	488.57	236.50	446.78	7.750	1.641	15.638
TOSHKA1 (G5)	577.62	340.00	245.24	882.86	605.00	334.21	497.49	-6.221	-4.403	13.237
Shndwell3 (G6)	559.05	511.60	383.17	943.50	445.07	403.17	540.93	-5.665	8.461	14.171
$H_{82}F_7$ (G7)	782.07	753.02	424.76	1110.95	658.74	418.40	691.32	-6.077	4.620	13.040
ZHR_{78} (G8)	640.95	585.07	311.90	786.36	661.60	233.02	536.48	2.584	-4.675	6.983
H102F58 (G9)	743.17	555.88	358.26	745.07	585.07	449.52	572.83	6.832	2.173	13.880
M261-1 (G10)	679.05	385.71	270.17	912.31	483.50	247.93	496.45	-5.956	4.666	12.830
H53F3-7 (G11)	639.52	613.33	375.24	954.93	697.14	419.69	616.64	-3.147	-3.153	7.058
SOHAG1 (G12)	766.98	637.62	424.76	702.55	570.79	406.22	584.82	10.708	4.610	21.975
Mean	676.44	556.81	358.50	869.64	620.80	374.84	576.16			
IPCA1"	3.54	2.92	3.14	-11.31	0.71	1.00				
IPCA2≈	2.94	1.23	3.18	1.57	-9.49	0.57				

Env: environment; IPCA: interaction principal component axes, ASV: AMMI stability values. IPCA1" for the environment. IPCA2≈ for the environment.

of Purchase *et al.* (2000) who affirmed that the lowest values of ASV refer to the most stable genotypes.

AMMI biplot

Graphical presentation of GEI using AMMI parameters is known as biplot, it is used to study the pattern of response of G, E, and GEI using main effect of means *vs* the IPCA1, and identify genotypes with broad or specific adaptation to target environments (Amiri *et al.* 2013). The authors added, genotypes with IPCA1 scores close to zero expressed general stability, whereas the larger scores representing more specific adaptation to environments. As shown in Fig 1, the points for environments are more scattered than the points for genotypes demonstrating that the variability resulted from applied environments were higher than that due to tested genotypes and this is in complete agreement of the AMMI analysis. Very little interaction effect was represented by Env5, it had mean seed yield above the grand mean value, and is considered as stable environment to test genotypes for seed yield. Env1 showed high interactive effect and high IPCA score compared to Env5 and considered less stable. In contrast, although Env3 and 6 showed low interactive negative effect for yield, they are characterized by their low mean yield below the grand mean value and least favorable environments for almost all genotypes. Based on biplot visualization, Env1, Env5 and Env4 are considered as favorable environments, while Env3 and Env6 are assigned as poor environments. Env 2 showed intermediate contribution to GEI, it is characterized as average environment. In accordance with other studies on classifying thirteen sesame genotypes across six tested environments (Tadesse and Abay 2011), our results confirmed the uniformity between the results of biplot with classification based on environmental grand mean.

As stated in previous study, either direction away from the biplot origin indicates greater GEI and reduced adaptability (Gauch 1992). Therefore, G1, G2, G3, G7, G11 and G12 was considered high greater yield producer than grand mean, while, G4, G5, G6 and G10 performed less yielding ability than overall mean value. Because genotypic stability is quite crucial in addition to genotype yield mean (Purchase *et al.* 2000), G1, G2, G3 and G11 are considered stable across different environments accompanied with high mean seed yield, in comparison with G7 and G12 which showed higher interaction effects and therefore presenting unstable performance. Genotypes G4 and G8 are adapted to low yielding environments, G8 showed less interactive effect (as also indicated by ASV value) and considered as stable to severe drought stress compared with G4.

GGE biplot

Ranking of 12 sesame genotypes based on their mean yield and stability performance was exhibited in Fig 2. As presented in the visualization, the line passing through the biplot origin is called the average environment coordinate (AEC), which is defined by the average PC1 and PC2 scores of all environments (Yan and Kang 2003).

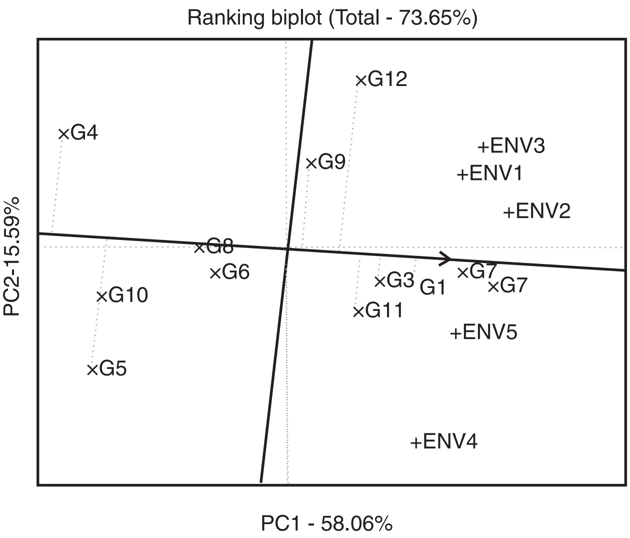

Fig 2 Average environment coordination (AEC) views based on environment-focused scaling for the means performance and stability of genotypes.

The yield stability of genotypes is measured by the line with double arrows which passes through the origin and is perpendicular to the AEC (Yan and Hunt 2001, Yan *et al.* 2000). In the same context it was reported that, stable genotypes have a shorter vector from the AEC, and the high yielding genotypes have the most distance on the right side of biplot from the confluence point of AEC and double arrow lines (Frashadfar *et al.* 2012). Therefore, genotype with longer projection to the AEC ordinate, regardless of the direction, represents greater GEI, and considered more variable and less stable across environments. Accordingly, G1, G7, G3 and G2 were considered the most stable genotypes as they had the shortest vectors, in addition the most yielding genotypes were G7 and G2 as they were the most distance from the right side of the biplot and their yield surpassed the environmental mean. Previous finding confirmed the critical importance of both stability and mean yield of genotypes (Purchase *et al.* 2000), therefore G7 and G2 were recommended as favorable genotypes from both mean yield and stability performance aspects. Genotype 12 demonstrated the lowest stability which possessed varying performance across environments, while G4 produced the least seed yield. For sesame breeding purposes, simultaneous selection for both seed mean yield and genotypes stability performance is an important consideration.

The present study highlights the seed yield stability of sesame genotypes from different sources using AMMI analysis and GGE biplot visualization. It is recommended that, genotypes: 1, 2, 3 and 11 as stable with high seed yield across the six tested environments. In contrast, G12 followed by G9 were highly interactive and recommended to be cultivated under favorable environments for seed yield production. G8 showed less interactive effect and considered as stable to severe drought stress.

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