Environment X Genetic Stability of Different Sorghum Bicolor Varieties/Promising Lines Under Various Environmental Conditions

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Received: 12/10/2021
Revised: 09/03/2022
Accepted: 26/03/2022

Abstract

Sorghum (*Sorghum bicolor* L. Moench) as an important food and fuel crop is undergone breeding for novel types, and its expansion into the new environments is necessary, however the efforts become complicated for breeders as well as agronomists to select for the best performing genotype in a particular environment due to unexpected, but significant genotype x environment interaction. This study was performed to thoroughly analyse the trade-offs between the agronomic performance and stability of sorghum genotypes produced under agro ecological conditions of Bahawalpur, Pakistan. Three sorghum lines i.e., G1 (S14), G2 (S22) and G3 (Jowar-86) were evaluated under eight environments which were formed by combining two sites of varying soil conditions (saline and normal soil) and were sown at four different sowing dates in order to determine the yield performance. Furthermore, AMMI analysis and GGE (generation×gene×environment) interactions were performed to identify the most stable variety for semi-arid environment. The results revealed that soil conditions significantly affect the grain yield of sorghum. The highest yield was obtained in E4 (1799 kg ha $^{-1}$) under normal soil conditions and the best performing line was identified as G1. While under saline/problematic conditions E3 gave mean yield of 1530 kg ha^{-1} while line G1 gave 1505 kg ha-1 of yield. As far as the AMMI and GGE analysis is concerned, significant value for scores of PCAs were obtained as PC1 (61.3%) and PC2 (38.7%) while GGE analysis also gave significantly different scores for PC1 and PC2 as 86.8 and 13.2% respectively. The genotype G1 had low PC1 scores (1.59) as compared to G2 and G3 and thus it was identified as most stable genotype. The environment (E3) and (E4) were highly correlated to each and (E6), (E8) were discriminatory environments for all tested genotypes.

Keywords: AAMI biplot, GGE interaction, *Sorghum bicolor*, problematic soil, Principal components.

Introduction

Climate change poses severe threats at global level which extensively disturbs the developing countries as they face countless vulnerabilities with lesser capacity to mitigate the negative impacts. Pakistan is amongst the developing countries and like most of them, its economics solely depends upon the agriculture sector. Hence, the farming sector of Pakistan is under the risk of current climate crisis. The country faces risky events of fluctuating precipitation, floods, dry spells and temperature convection which affects water and land resources negatively (Kurukulasuriya, et al., 2006; Mendelsohn, 2014). Hence, eventually Pakistan is at threat of food insecurity and water shortage (Ali et al., 2017; Anum et al., 2021). The continuous alteration in environmental conditions, the areas which are water scared will ultimately become drier and hotter. Runoff patterns are also unpredictable owing to uncertain changes in rainfall intensity and pattern. Such circumstances create obstacle in development and maintenance of soil aggregates, disturbs soil physical and chemical properties, alters water infiltration rates and influences soil compaction, aeration and erodibility. One of the most deteriorating consequences can be soil salinization which threatens the present cultivars of various crops of significant importance (Imran, 2018). Sorghum (*Sorghum bicolor* L. Moench) is amongst with the economically distinctive cereal crop with high grain production rates (Iqbal et al., 2010). In Pakistan, sorghum is cultivated both as fodder and grain crop and ensures the sustainability of agricultural community. Being grown as a kharif crop (Habib, & Tahir, 2013), the phenolic profile of sorghum is exceptionally unique, abundant and diverse than other cereal grains. The phenolic compounds in sorghum plant comprised of phenolic acids, 3-deoxyanthocyanidins, and condensed tannins (Xiong et al., 2019).

It is crucial to develop sorghum genotypes which are high yielding and stable, therefore, they can be adapted to a wide range of locations. The success of any variety/hybrid is anticipated by its growth and development stability under the varying environmental conditions and its inherent yielding capacity. The desired hybrid is the one which can adapt to broad growth conditions with above and below variance in a given area of production. Hence, it is required to identify the varieties which have high yield potential under constructive environment as well as during the stress conditions (Al-Naggar et al., 2018).

The Additive Main effects and Multiplicative Interaction (AMMI) is a model that analyze the multi environmental yield trials. It helps in understanding the complex relationship between the varied environments and performance of genotypes throughout to appraise and envisage the accuracy of genotypic performance (Gauch, 2013). The genotype and environment interaction, commonly known as GGE is described as the ranking of different genotypes under various environmental conditions (Sayar et al., 2013). These anaylsis are performed for the improvement in selection criteria for genotypes, their relative ranking and provides insight to the superiority of a given variety (Mumtaz et al., 2019). The genotype main effects+genotype x environment interactions (GGE) are a type of statistical analysis that is commonly used by breeders and effective method based on principal component analysis for exploring multi environment trials (Yan et al., 2008). However, GXE is defined as the interaction between the two factors i.e., genotypes and environment. GxE deals with their interaction only. The GxE is influential on grain yield (Admas & Tesfaye, 2017; Adugna, 2007; Nida et al., 2016), nutritional quality and nutritive contents of a crop (Beta & Corke, 2001; Wirnas et al., 2015). It also impacts the physiochemical properties and total soluble solids in sorghum (Palé et al., 2010; De Souza et al., 2013). Hence, this study is carried out to evaluate the yield ability and adaptability of three locally developed sorghum genotypes grown in eight different environmental conditions. The objective of this research is to analyse the grain yield of sorghum under AMMI and GxE Models for identification and further quantification of suitable and sustainable sorghum varieties as well as identification of most stable environments considering the appraised varieties.

Material and Methods:

Experimental site:

An experiment was carried out at Regional Agricultural Research Institute, Bahawalpur, Pakistan, during 2019 and 2020. The study site is located at 29.3544° N, 71.6911° E and 214 m above sea level. It experiences an average annual temperature of 26.1°C with an annual rainfall of 223 mm.

Treatments and Experimental design

Three sorghum lines/varieties viz S-14, S-22 and jowar-86 were tested in this experiment. Further two experimental sites were selected at the farm area of Research station. The soil of one site was problematic in nature with more salt contents while the soil of second site had normal characteristics. Both sites were distinguishable on the basis of salt contents and named as saline soil and normal soil respectively. The results of the soil analysis done prior to the crop sowing are depicted in the Table 1.

Table 1. Soil analysis of both sites prior to crop sowing

Soil used in experiment	Depth (inches)	EC dS m^{-1}	pH	OM (%)	Available K (ppm)	Available P (ppm)	Textures
Normal soil	0-6	3.2	8.3	0.59	116	7.8	Loam
	6-12	2.9	8.2	0.54	110	7.4	Loam
Saline soil	0-6	4.1	8.4	0.58	110	7.7	Loam
	6-12	3.7	8.2	0.54	108	7.4	loam

The sowing was done at four different sowing dates thus, a total of three interactive factors were made (four sowing dates, two soil conditions and three varieties). Altogether, eight contrasting environmental conditions were made viz. E1 (25 June-saline soil), E2 (25 June-normal soil), E3 (5 July-saline soil), E4 (5 July-normal soil), E5 (15 July-saline soil), E6 (15 July-normal soil), E7 (25 July-saline) and E8 (25 July-normal soil). As the average weather conditions were different for each sowing dates hence, they were distinguished as environment. The meteorological details during the duration of study were noted regularly and are presented in Figures 1 (a) and (b). The trial was arranged in split plot design. The main plots comprehended soil types whereas, sub plots comprised of varieties. Each sowing date was sown in the similar design. The plot size was maintained as 3x7 m and the experiment was replicated three times. All the cultural and crop production practices were kept constant for each treatment and sowing was done according to the prescribed schedule for both years.

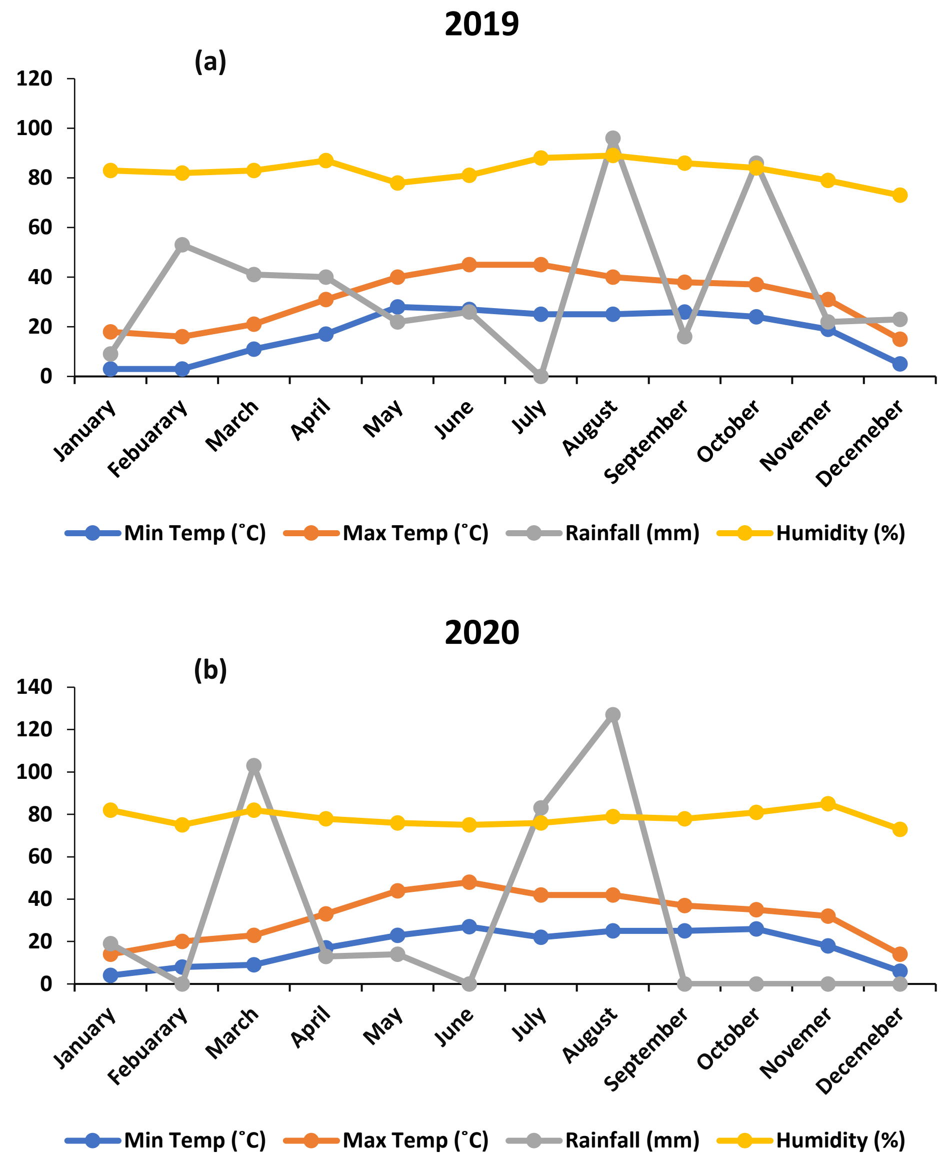

Figure 1. Weather data during the year (a) 2019 and (b) 2020.

Additive mean effect and multiplicative interaction (AMMI) model

The stability analysis was carried out by subjecting the data to statistical software Pb tools. AMMI stability method was used which is described by Zobel et al (1988) is as follows:

$$Yij = \mu + gi + e_{j+} \sum_{k=n}^{n} \lambda k \;\; \alpha ik \mathrm{yjk} + rij + \varepsilon \mathrm{ij}$$

where Yij is the mean response of genotype i in environment j; μ is the overall mean; gi is the fixed effect of genotype i (i = 1, 2, . . . g); ej is the fixed effect of environment j (j = 1, 2, . . . e); εij is the average experimental error; G × E interaction is represented by the factors; λk is a unique value of the kth interaction principal component axis (IPCA), (k = 1, 2, . . . p, where p is the maximum number of estimable main components), αik is a singular value for the ith genotype in the kth IPCA, yjk is a unique value of the jth environment in the kth IPCA; rij is the error for G × E interaction.

Results and Discussion

Effect of environment on yield of sorghum

The results of this experiment reveal that soil condition is critical for determining the final yield of a crop. During both years, saline soil significantly reduced the overall grain yield. Similarly, the tested genotypes showed significantly different results with respect to sowing time. The genotype S14, produced maximum grain yield 1753 kg ha^{-1} in normal soil conditions whereas the minimum grain yield as 1072 kg ha^{-1} was obtained in Jowar-86 in saline soil conditions. As far as the sowing time is concerned, all genotypes performed significantly different in terms of yield. For both soil conditions the best sowing date was 5 July. The grain yield results are depicted in Table 2 (a, b).

Table 2 (a). Grain yield kg ha^{-1} (2020)

Saline soil					Normal soil			
	Varieties/ Genotype				Varieties/ Genotype			
Sowing dates/ environment	V1 (S14)	V2 (S22)	Jowar-86	Mean	V1 (s14)	V2 (s22)	V3 (jowar 86)	Mean
SD1	1138	1014	968	1040 B	1560	1061	911	1177.4 B
SD2	1419	1376	1194	1329 A	1806	1590	1393	1596.3 A
SD3	1137	1084	1022	1081 B	1491	1338	1130	1319.6 A
SD4	845	784	922	850 C	1153	852	1008	1004.3 B
Means	1134 A	1064 B	1026.5 B		1502.5 A	1210.2 B	1110.5 C	
LSD for sowing date= 226 LSD for varieties= 234					LSD for sowing date= 266 LSD for varieties =111			

Table 2 (b). Grain yield kg ha^{-1} (2019)

Saline soil					Normal soil			
Sowing dates/ Environments	Varieties/Genotypes				Varieties/genotypes			
Sowing dates	V1 (S14)	V2 (S22)	V3 (Jowar-86)	Means	V1 (s14)	V2 (s22)	V3 (jowar 86)	Means
SD1	1637	1014	968	1207 B	1660	1061	968	1230 B
SD2	1799	1476	1314	1530 A	2006	1799	1591	1799 A
SD3	1337	1222	1084	1214 B	1891	1637	1130	1553 A
SD4	1245	784	922	984 C	1453	853	1107	1138 B
Mean	1505 A	1124 B	1072 B		1753 A	1337 B	1199 C	
LSD for varieties= 234 LSD for sowing dates =226					LSD for varieties= 111 LSD for sowing dates=226			

GE Analysis by AMMI model

The yield data was subjected to Stability analysis. The data was partitioned into three Principal components. The subsequent ANOVA produced through AMMI and GGE PCAs is presented in Table 3. The AMMI analysis shows the total variations occurs, in the form of PC1 and PC2 as 61.3% and 38.7% of total variation respectively. Subsequently, biplots were generated as AMMI1 in which IPCA1 and additive main effects were plotted against each other and AMMi2 in which IPCA1 and IPCA2 were plotted against each other. They illustrate the environment and genotype effects simultaneously (Figure 2 a, b)

Table 3. ANOVA for principal components AMMI and GGE analysis for grain yield kg ha^{-1}

	percent	acum	Df	Sum.Sq	Mean.Sq	F.value	Pr.F
AMMI ANALYSIS							
PC1	61.3	61.3	8	368808.3	46101.04	4.325429e+18	0
PC2	38.7	100.0	6	232875.5	38812.58	3.641590e+18	0
PC3	0.0	100.0	4	0.0	0.00	0.000000e+00	1
GGE ANALYSIS							
PC1	86.8	86.8	8	2423207.9	302901.0	2.841968e+19	0
PC2	13.2	100.0	6	367682.4	61280.4	5.749633e+18	0
PC3	0.0	100.0	4	0.0	0.0	0.000000e+00	1

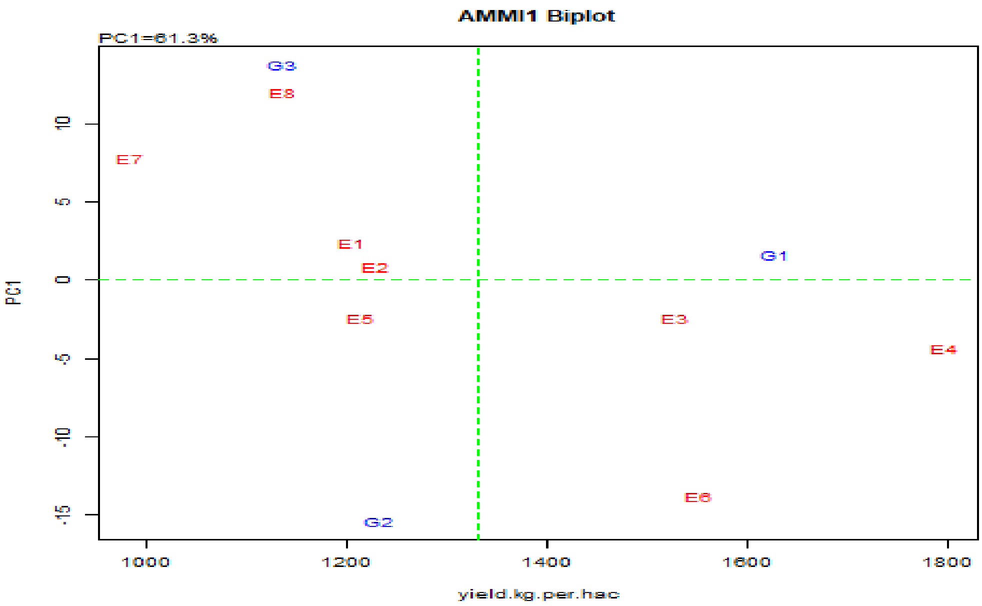

Figure 2 (a). AMMI biplot1 is produced when PC1 is computed with the yield kg ha

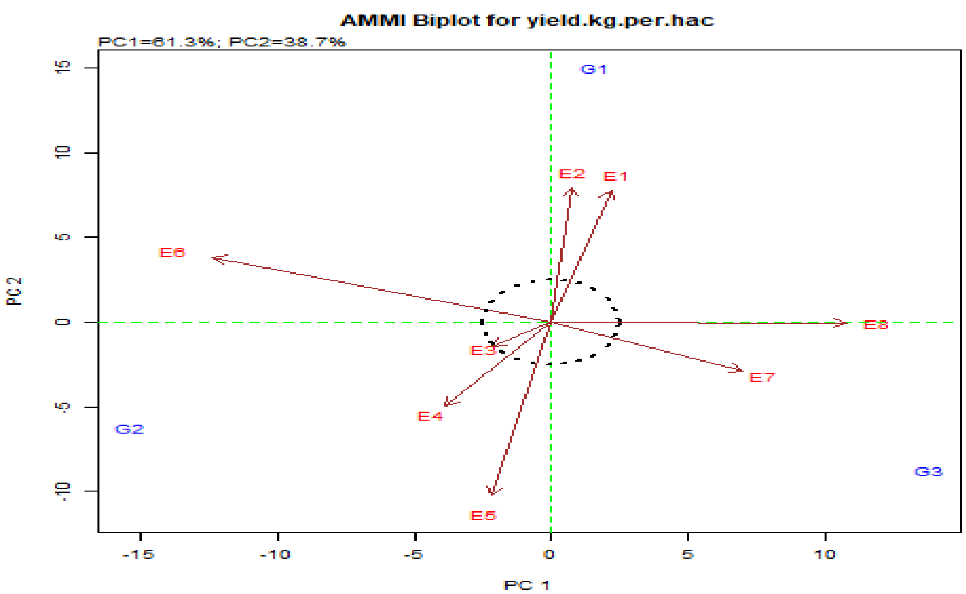

Figure 2 (b). AMMI2 biplot2 is produced when PC1 is computed with the PC2 scores zn AMMI2 biplot, the IPCA1 and IPCA2 scores of genotypes and environments (Table 4) were plotted against each other and depicted easy visualization of differences in interaction (Figure 1b). The AMMI2 biplot graph showed that E3 was the most favourable and ideal environment for the sorghum genotypes followed by E4. Whereas E7, E2, E1 were the average environments. However, E6 and E5 were found to be environments for the tested set of genotypes. Our results also showed that E5, E6 and E8 were located far away from the origin thus identified as discriminatory. Among the studied genotypes G1, G3 and G2 had low to high values of IPCA1 (Table 4) and similar results were reported previously regarding the stability of genotypes about low values (Mohammadi et al. 2013, Erol et al. 2018). The three tested genotypes were located far away from the origin hence it was difficult to draw conclusion graphically, however, the IPCA1 values identified G1 as the most stable one among the tested environments.

Table 4. IPCA 1, IPCA2 scores and environment means of grain yield over 8 environments and 3 genotypes

Level	Yield kg ha^{-1}	PC1	PC2	PC3
G1	1629.08333333333	1.59876068160796	15.0151723536212	1.53993548484517e-07
G2	1231.18333333333	-15.386857562374	-6.2733597155497	1.53993548484516e-07
G3	1136.03333333333	13.7880968807661	-8.74181263807149	1.53993548484516e-07
E1	1207.15555555556	2.41116041050634	8.64056521814003	-1.75198519024641e-07
E2	1230.22222222222	0.844013585019949	8.80742928522417	1.35461835272035e-07
E3	1530.08888888889	-2.40842780871853	-1.59982995675428	6.87032660287405e-10
E4	1799.2	-4.31908745535113	-5.49298697256716	-7.09655675275532e-08
E5	1214.84444444444	-2.44069734619776	-11.3258120621767	-2.49592666739913e-08
E6	1553.15555555556	-13.7755770760765	4.21917426463576	-7.91888230341182e-08
E7	984.177777777778	7.73508745429941	-3.1919490281632	6.96601965620599e-09
E8	1137.95555555556	11.9535282365183	-0.0565907483386272	-1.00591575870929e-07

IPCA=interaction principal component

To understand the capacity for adaptation of different G × E and environments compared; we ranked the eight environments on the basis of grain yield. The relationship between the environments is determined by the angles present between their vectors. Also, the correlation among the environments can be predicted from the cosine of the angles between the vectors (Yan and Tinker, 2006). For grain yield, E1S1 and E2S2 were highly correlated, and the results are depicted in Figure 3. Genotypes or the environments located at the right-hand side of the midpoint of the axis (IPCA1) represents higher yields as compared to those which are present on the left-hand side (Ngeve, & Bouwkamp, 1993). In our study, genotype G1 (Figure 4) was generally high yielding as it was placed on right-hand side of midpoint of IPC1 axis (representing grand mean). Genotypes 2 and 3 were present into sectors that does not contain any location. This indicates that these genotypes are poorly adapted to all environments tested. However, all the locations which exists in one sector with the best-performing genotype can be considered as mega environment for that genotype (Gebre, & Mohammed, 2015).

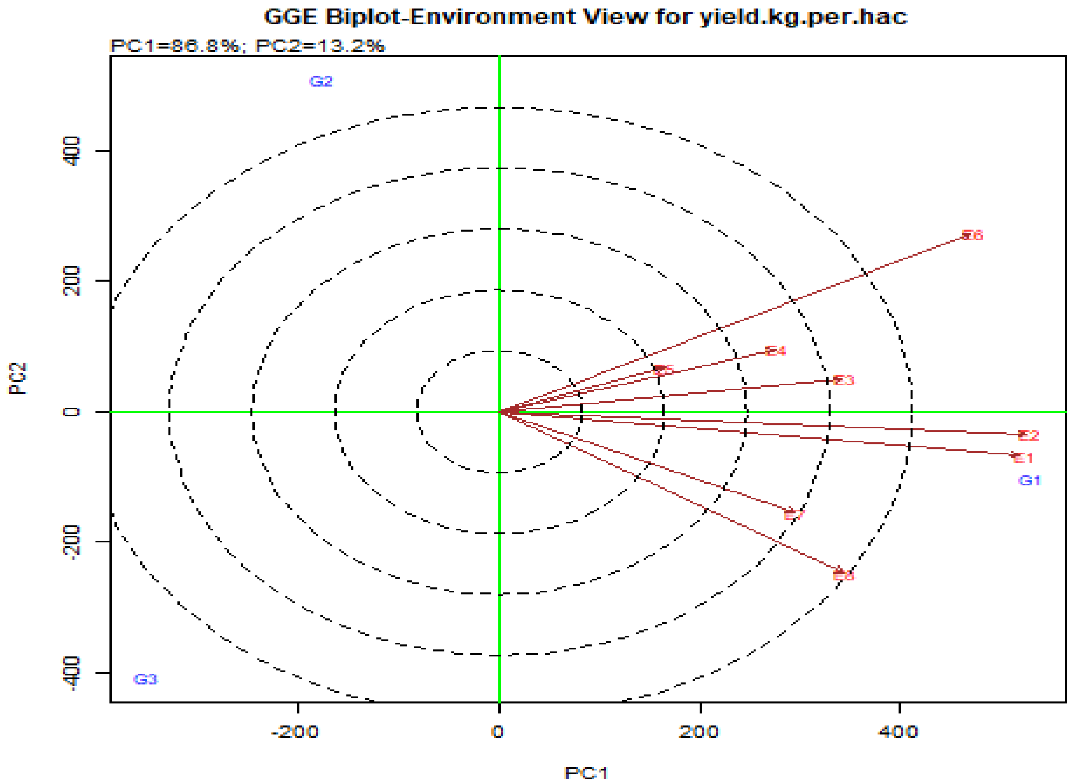

Figure 3. Environmental evaluation

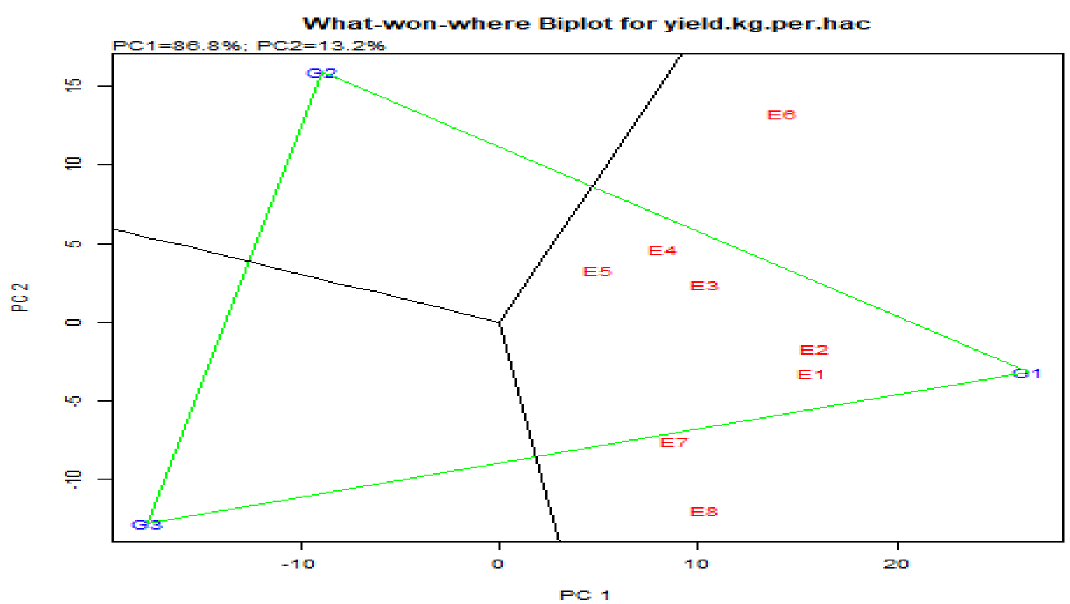

Figure 4. What-won-where biplot

Furthermore, GGE analysis identifies the best Genotype in each environment and assesses the stability of genotype. One of the most imperative and attractive feature of GGE is its which-won-where plots which shows crossover GGE interaction, differentiates mega environments and specifies genotype adaptability (Rakshit et al. 2014, Erol et al. 2018). Yan and Tinker (2006) also states that it is important to study any crop in multi environment to know its mega environment. Our results showed strong correlation amongst the environments present in the same sector. Erol et al (2018) affirmed a resilient environmental influence and mega environment presence by virtue of variations observed in genotype performance and sector wise categorization. As, GGE biplots are helpful in environment assessment since it shows discriminating ability of environments and provides representative of GGE view, hence Yan et al (2007) and Aktas (2016) stated that GGE is advantageous over AMMI biplot analysis. The ANOVA revealed a significant difference between genotypes, environment as well as their interaction. It indicates that the tested varieties performed differently at each site. It is anticipated that difference in soil type and chemical properties, the varied temperature and rainfall occuring during the specific crop period is responsible for the difference. Ideal cultivars and environments are those which have large PC1 scores (high mean yield) and small PC2 scores (high stability) (Frashadfar, Safari, & Jamshidi, 2012). A variation was found in genotype performance under the test environments hence contributed in high GEI variability. The similar results were reported previously which stated that GEI reduce the efficacy pose by genotypes by confounding to their yield potential, hence it is important to evaluate the genotypes and multi environments for testing the genotypes.

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الاستقرار الوراثي والبيئي لأنواع الذرة الرفيعة المختلفة/السلالات واعدة تحت الظروف البيئية المختلفة

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المُستَخلَص

تاريخ استلام البحث: 2021/10/12
تاريخ تعديل البحث: 2022/03/09
تاريخ قبول البحث: 2022/03/26

الهدف: يعتبر السرغوم والذي يُعرف علمياً بـ Sorghum bicolor L. Moench محصول هام يساهم بشكل كبير في تلبية احتياجات الغذاء والوقود في جميع أنحاء العالم، ونظراً للتغير المستمر لدرجة الحرارة على الكرة الأرضية ، حدث تغيير درجات الحرارة وتغير المناخ في أماكن كثيرة، ويحتاج هذا النبات إلى البحث عن الجينية الجديدة، والتي تستطيع تلائم مع البيئة الجديدة بشكل أفضل، ويساهم في الارتفاع في الجودة والمحصول النهائي لهذا النبات، ويحتاج هذا الأمر إلى التغيير في التركيب الوراثي ، وقد تم عقد إجراء دراسة شاملة لمعرفة الأداء الزراعي واستقرار النمط الجيني لسرغوم (الذرة الرفيعة) المنتجة في ظل الظروف الإيكولوجية الزراعية في منطقة بهاولبور، الواقعة بإقليم البنجاب في باكستان.

الأسلوب: تم تقييم ثلاث سلالات سرغوم أي جي-1 (ايس-14)، جي-2 (ايس-22) وجي-3 (جوار-86) تحت ثماني بيئات تشكلت من خلال الجمع بين موقعين من ظروف التربة المختلفة (التربة المالحة والعادية) وزُرعت في أربعة مواعيد الزراعة المختلفة لتحديد أداء المحصول. علاوة على ذلك، تم إجراء تحليل **AMMI** وتفاعلات **GGE** من أجل تحديد الاصناف الأكثر استقرارًا للبيئة شبه القاحلة.

النتيجة: أوضحت النتائج أن ظروف التربة تؤثر بشكل كبير على محصول حبوب السرغوم (الذرة الرفيعة). تم الحصول على إنتاجية مرتفعة في أي-4 (1799كيلوغرامات للهكتار) تحت ظروف التربة العادية وتم تحديد السلالة الأفضل أداءً هو جي-1. وكذلك في ظل الظروف الملوحة / الإشكالية، أعطى أي-3 إنتاجية متوسطة 1530 كيلوغرامات للهكتار بينما أعطى السلالة جي-1 إنتاجية 1505 كيلوغرامات للهكتار. فيما يتعلق بتحليل **AMMI** و**GGE**، تم الحصول على القيمة الكبيرة لدرجات PCAs مثل 16.3%) **PC1**) و 38.7%) **PC2**) بينما أعطى تحليل **GGE** أيضًا درجات مختلفة بشكل كبير لكل من PC1 و PC2 حيث بلغتا 86.8 و 13.2% على التوالي. كان للنمط الجيني جي-1 درجات منخفضة من 1.59) PC1) بالمقارنة مع جي-2 وجي-3 وبالتالي تم تحديده كالنمط الجيني الأكثر استقرارًا. كانت البيئة (أي-3) و(أي-4) مترابطة إلى حد كبير مع كل منها، و(أي-6) و(أي-8) كانت بيئات تمييزية لكل أنماط جينية مختبرة.

الخاتمـة: يمكـن أن يوفـر اسـتقرار النمـط الجينـي عبـر بيئـات مختلفـة النتائـج المهمـة بشـكل كبيـر التـي تسـاعد المربيـن علـى تحديـد المـادة الوراثيـة الأكثـر ملاءمـة وقابليـة للتكيـف مـع مناطـق معينـة.

مفاتيـح الكلمـات: AAMI biplot، تفاعـلات **GGE**، الـذرة الرفيعـة، التربـة ذات المشـاكل، المكونـات الرئيسـية.