Genotype x environment interaction and stability analysis of grain sorghum (*Sorghum bicolor (*L.) Moench) yield under rainfed and irrigation conditions in central Sudan

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ABSTRACT

An experiment was conducted over three consecutive seasons (2009, 2010, and 2011) at three locations , Rahad Research farm. Gedarif Research Station farm (North Gedarif and South Gedarif region) of the Agricultural Research Corporation (ARC), Sudan. Both North and South Gedarif were rainfed, while Rahad station was irrigated. A randomized complete block design with four replicates was used. Sorghum production is highly influenced by the environment where it is grown, thus, the genotype by environment interaction is highly significant when breeding for specific adaptation. The objective was to assess the genotype x environment interaction and stability of grain yield. The mean squares due to environment, genotypes and genotype x environment interaction were highly significant for grain yield. Significant differences among genotypes for the studied characters were found in almost all seasons, indicating that these sorghum genotypes were highly variable for the characters studied and , therefore, expected to respond to selection. The interaction effects of genotype x location were highly significant for most traits indicating that genotypes responded differently to different environments and some are environmentally specific. The present study showed that the first two axes PCA1,PCA2 in Additive Main Effect and Multiplicative Interaction (AMMI) accounted for the GE sum of squares by 56.7% and 19.3%, respectively, while the regression analysis accounted for GE sum of squares by 21.9% .Hence, AMMI analysis was superior to regression techniques and more effective in partitioning the interaction sum of squares. From both statistical stability models used in this study, i.e. Eberhart and Russell (1966) as well as the Aditive Main Effect and Multiplicative Interaction (AMMI) analysis, they pointed out that genotypes Mugod (1510 kg/ha), Tabat (1299 kg/ha), Wad-Ahmed (1471 kg/ha), Gadambalia bloom (1428 kg/ha), Safra (1410 kg/ha) and Tetron (1323) were high yielding and stable under the favorable environments of South Gedarif and Rahad irrigated Scheme. Genotypes Wad Baku(1225 kg/ha), Farhoda (1252 kg/ha),Gesheish (1194 kg/ha) and Wad Fahal (1230 kg/ha) were low yielders but quite stable under low rainfall environments like North Gedarif environment.

INTRODUCTION

Sorghum (*Sorghum bicolor* (L) Moench) is an important food and feed crop. As an energy supplier for the world's population, it ranks sixth, and it is fifth in importance among cereals. Semi-arid tropical Asia and semi-arid tropical Sub-Saharan Africa grow about 60% of the world area (ICRISAT and FAO, 1996), while Sudan grows about 24% of Africa area and produces 17% of its production. The national average yield in the Sudan (250 kg/fed) was 18% of that obtained at the research stations (Ishag and Ageeb 1987). This was attributed among many other factors, to the use of low yielding cultivars as well as to poor cultural practices.

During the last 15 years, plant breeders in the Agricultural Research Corporation (ARC) have successfully developed high yielding open pollinated varieties such as Feterita, Wad Ahmed, Ingaz (Osman and Mahmoud,1992) and Tabat (Osman *et al*.1996). In addition, many other varieties suitable for both irrigated and rainfed sectors were also developed such as Butana and Bashayer (Elzein *et al*.,2008), and AG-8 (Abdalla *et al*., 2009).

Estimation of stability performance has become an important tool to identify consistently high-yielding genotypes (Kang,1998). Many stability statistical methods have been used to determine whether or not cultivars evaluated in multi-environment trials were stable (Lin *et al*.,1986; Flores *et al*.,1998; Hussein *et al*.,2000; Robert,2002).The use of a method that integrated yield performance and stability for superior genotypes becomes important because the most stable genotypes were not often the highest yielding (Kang and Magari ,1996).

Conventional methods of partitioning total variation into components due to variety, environment and variety-environment interaction conveyed little information on individual patterns of response (Kempton ,1984). Other methods used include regression analysis to partition genotype x environment interaction (Gauch,1988), and multivariate analysis (Westcoff,1987). Development of sorghum with high yielding and desirable grain quality for different environments is one of the exciting research that leads to successful evaluation of stable genotypes which could be used for general cultivation or as breeding material. Therefore, the objective of this study was to assess genotype x environment interaction and stability of sorghum grain yield using regression method of Eberhart and Russels, (1966). The deviation from regression is used to assess unpredictable part of variability

of any genotype with respect to environment that could not be predicted by the regression. It is a measure of reliability of the linear regression and the stable genotype was defined as one with b_i = 1, S^2d = 0 and higher than the overall mean grain yield , and more recent application methods such as Additive Main and Multiplicative Interaction analysis (AMMI). Multivariate analysis such as AMMI analysis groups genotype or environments in a qualitative manner according to their similarity of performance rather than quantitative manner of the stability parameters. AMMI analysis involves the clustering analysis to classify genotypes under the most adapted sites for them depending on the AMMI principle components scores (Gauch and Zobel,1988; Nachit *et al*. 1992). Non parametric approach (multivariate) has been proposed to overcome problems associated with parametric approach (Lin *et al*,1986).

MATERIALS AND METHODS

Location

The experiments were conducted over three consecutive seasons (2009, 2010 and 2011) at three locations,*viz*. Rahad Research Farm , North and South Gedarif regions of the Gedarif Research Station farm of the Agricultural Research Corporation (ARC), Sudan . The three locations lied within the central clay plain of the Sudan, characterized by heavy alkaline clay soil, with a pH of around 8.5 and low in nitrogen and organic matter.

Plant material

Eighteen accessions of sorghum collected from Gedarif and from the gene bank (Wad Medani) were used in this study. These accessions were five released varieties (Wad-Ahmed, Tabat, Butana, Bashayer and Arffagadamak-8), and 13 local land races preferred by farmers (Korakollo, Mugod, Saffra, Wad-Bako, Tetron, Faki-Mustahi, Farhoda, Gadambalia bloom, Ajeb-seido, Arafah, Gesheish,Wad-fahal and Milo) .

Cultural practices

The standard cultural practices adopted for sorghum at the ARC were followed. Land was prepared by disc ploughing, disc- harrowing, leveling and ridging in irrigated site and by disc-harrowing in rain-fed sites. Treatments were laid out in a randomized complete block design with four replicates in the different locations and seasons. Sowing was done in the

first week of July under irrigation and the first to the third week of July under rainfed conditions depending on the onset of rainfall. Under irrigation, the entries were sown in five rows, 5 m long on ridges; 0.8 m apart at 0.3 m intra - row spacing and thinned to two seedlings per hill. Under rainfed conditions, they were also sown in five rows 5 m long on flat; 0.8 m apart at 0.2 m intra row spacing and thinned to two seedlings per hill. Urea at the rates of 80 kg and 40 kg /fed was applied under irrigation and rainfed sites, respectively, as recommended by the ARC. The crop was irrigated every two weeks or whenever necessary and irrigation was withheld three weeks before harvest. In irrigated and rainfed experiments, assessments were made in the central three rows of the plot discarding one row or more at each side. Data were collected on days to 50% flowering, plant height, number of heads/m^2, head length (cm), head width (cm),1000 seed weight(g) and grain yield (kg/ha).

Statistical analysis

The analysis of variance procedure was used to test differences among genotypes within each season, location and combined**.** Eberhart and Russell (1966) stability model was performed. In addition, the Additive Main Effect and Multiplicative Interaction (AMMI) was carried out to show the stability and pattern of adaptation of sorghum genotypes in nine environments, using IRRISTAT(2005) statistical analysis package for grain yield data.

RESULTS AND DISCUSSION

The combined analysis of variance showed highly significant differences among seasons for all the traits studied with the exception of head length (Table 1).It also showed that differences among locations were highly significant for all traits under study. Differences among genotypes were highly significant for all traits with the exception of number of plants/m^2 and head length. The interaction effect of genotype x location was highly significant for most traits except number of plants /m^2 and number of heads /m^2 and this may be due to genetic factors.

The significance of genotype x environment indicated that genotypes responded differeenvironment interaction for all studied traits. From the present study, and on the basis of the importance of genotype x environment interactions as shown it could be concluded that sorghum genotypes show differential responses when grown under different environments, suggesting that these genotypes should be tested in different environments.

Table 1. Means for seasons , locations ,genotypes and their interactions for18 sorghum genotypes combined over three seasons and three locations, grown at North Gedarif, South Gedarif, and Rahad Research farm (RRF) during season 2009,2010,and 2011.

Trait	Season (S)	Location (L)	Genotype (G)	L X G	S X G	S X LXG
DF	2068**	7091**	1274**	126**	245*	141**
PH	19500**	246696**	1323**	2057**	2333**	1775**
P/m	55**	909**	7.84 ns	9.60 ns	9.11ns	7.93 ns
H/m	83.9**	4096**	28.7**	7.67 ns	13.3**	10.30*
HL	573 ns	15.5**	29834 ns	18.84**	56.23**	22.83**
HW	74.8**	75.2**	2.5**	1.8**	1.13 ns	1.5**
Sw/	660**	7251**	423**	113**	55**	46**
GY	24873664**	7349446**	166993**	165846**	165846**	143870**

*,** Significant at 0.05and 0.01 of probability levels, respectively; ns=not significant.
DF= days to 50% flowering, PH= plant height (cm), P/m= number of plants /m²,
H/m²=number of heads /m²,HL= head length (cm), HW=head width (cm),Sw (g)
= 1000 seed weight (g) , GY=grain yield (kg/ha).

Grain yield stability

The data on the three stability parameters, mean performance, regression coefficient(bi) and deviation from regression (S^2d) for grain yield are presented according to Eberhart and Russell (1966) stability model (Table 2). The mean grain yields of sorghum genotypes ranged from 846 kg/ha as minimum to the 1510 kg/ha as maximum , with an average of 1302 kg/ha. Seven genotypes recorded higher yield than the mean of all genotypes (Table 2).These genotypes were Tetron (1323 kg/ha), Butana (1333 kg/ha), Safra (1401 kg/ha), Gadambalia bloom (1428 kg/ha), Wad-Ahmed (1471kg/ha), Bashaiyer (1503 kg/ha), and Mugod (1510 kg/ha).

Genotypes with bi > 1 and mean grain yield greater than the general mean, were Mugod, Safra, Tetron, W-Ahmed and Gadambalia bloom indicating that they were more responsive to environmental changes and, therefore, suitable for favorable environments of irrigation conditions (Rahad) and high rainfall conditions (South Gedarif).

These findings agreed with those reported by Elasha *et al*. (2011) who studied stability and adaptability of seven hybrids and three open pollinated varieties under twelve environments. They found that the genotypes DIA-07666, DMN 15P 1003, PAC-501higher(S^2d) observed for Gew 22-15 and Gew 3-2 with mean grain yield below the general mean yield, indicating that these two lines were not stable under adverse conditions but may respond better to favorable environments.

The most stable genotypes as indicated by this stability parameter were Mugod, Tabat, Gadambalia bloom, Safra, Wad Ahmed and Tetron when the mean yield, regression coefficient and the deviation from regression were considered together.

Table 2 .Stability parameters for grain yield (kg/ha) of 18 sorghum genotypes tested at North Gedarif, South Gedarif, and Rahad during 2009,2010,and 2011 growing seasons.

Genotypes	Yield (kg/ha)	bi	S^2d
Korakollo	1272	1.07	4.7
Mugod	1510	1.58	11.4
Safra	1401	1.16	5.5
Wad Baku	1225	0.96	2.3
Tetron	1323	1.14	9.0
Faki Mustahi	846	0.75	2.3
Farhoda	1252	1.01	1.0
Gadambalia bloom	1428	1.18	5.7
Ajeb seido	1261	0.83	2.8
Arafa	1298	0.73	3.3
AG-8	1214	0.59	1.4
Butana	1333	0.97	1.2
Bashayier	1503	0.94	8.4
Tabat	1299	1.16	2.5
Wad Ahmed	1471	1.26	3.2
Gesheish	1194	0.92	5.5
Wad Fahal	1230	0.95	6.6
Milo	1286	0.72	3.5
Mean	1302		

bi =slopes of regression , S^2d =Deviations from regression.

In the present study, multivariate analysis such as AMMI analysis groups genotype or environments in a qualitative manner according to their similarity of performance rather than quantitative manner of the stability parameters. AMMI analysis involves the clustering analysis to classify genotypes under the most adapted sites for them depending on the AMMI principle components scores (Gauch and Zobel,1988;Nachit *et al*. 1992). The combined analysis of variance according to the AMMI model is presented in Table 3.

The partitioning of GE interaction through AMMI model analysis revealed that the four multiplicative terms (PCA1, PCA2, PCA3, and PCA4) were significant and were captured 56.7%, 19.3%, 10.1%, and 7.2% of variation due to GE interaction sum of squares, respectively. Together they accounted for 93.3% of GE interaction sum of squares. However, most of the variation was explained by the first principle components (PCA1).

According to Crossa *et al*. (1990), AMMI with two, three or four PCA1 axes is the best predictive model. Similarly, in the present study, the AMMI analysis further revealed that the first two interaction principle component axes (PCA1 and PCA2) explained 76% of the GxE sum of squares. This was in agreement with Sneller *et al*., (1997),who suggested that GxE pattern is collected in the first principal components of analysis.

Table 3. AMMI analysis of variance of the significant effects of genotypes (G), and environment (E) and genotype- environment interaction (GE) on grain yield (kg/ha) and the partitioning of the GE into AMMI scores.

Source of variation	DF	SS	MS	Efficiency (%)
Environment	8	0.25367E+0.8	0.317095E+0.7	
(E)	17	706700	41570.6	
Genotypes (G)	136	0.604554E +0.7	44452.5	100
GE I	24	0.342852E +0.7	142855***	56.7
PCA1	22	0.116852 E +0.7	53114.5***	19.3
PCA2	20	615978	30798.9**	10.1
PCA3	18	392181	21787.8**	07.2
PCA4	52	440344		
Residual				

,* Significant at the 0.01 and 0.001 probability levels, respectively.
DF, degree of freedom; SS sum of square, MS mean square and Efficiency % of GE sum of squares.

Variation among the studied genotypes for grain yield and their reactions to the environments were determined (Table 4). The highest average yield was obtained in E-7 followed by the E-9 (representing Rahad environment), whereas E-1 (representing North Gedarif environment) had obtained the lowest grain yield. E-7 exhibited the largest absolute PCA1 score (i.e. had the highest interaction effect), whereas the smallest score was shown by the E-4 (representing South Gedarif environment) (i.e. had the least interaction effects). Based on AMMI biplot, G and E having PCA values close to zero have small interaction effects, whereas those having large positive or negative PCA absolute values largely contribute to GE interaction. Hence, E-7 was the most interactive, while E-4 was the least interactive among the nine environments.

Table 4. PCA1 and PCA2 scores for the nine growing environments of sorghum genotypes.

Environment	E-Mean	IPCAe (1)	IPCAe (2)
E1	113.8	3.51928	6.33557
E2	144.3	3.39088	6.43972
E3	310.3	5.28205	-4.16294
E4	631.2	-3.50394	4.74171
E5	671.1	5.81292	17.75241
E6	475.3	7.83628	-1.66849
E7	1215.9	-39.053	-5.03838
E8	191.4	4.84558	0.39725
E9	1184.2	11.86991	-24.7968

E1,E2,E3 (North Gedarif),E4,E5,E6 (South Gedarif),E7,E8,E9 (Rahad).

To analyze genotype-environment interaction and adaptation graphically, AMMI biplot was used with the PCA score plotted against the mean yields (main effects).

A graphical display of the GE interaction of PCA1 and their effects (yields) is useful for revealing favorable pattern in genotypes response across environments (Crossa et al.1990). The AMMI bi-plot of mean on yield explained a large proportion of the treatment sum of squares. The PCA scores, negative or positive, more specific or adaptive genotype to certain environments. The more PCA score approximate to zero, the more stable or adapted genotype over all environments. Accordingly, the genotypes Mugod, Safra ,Tetron, Gadambalia bloom, Butana ,and Bashaiyer revealed good stability across environments and high grain yields. This indicated that these genotypes Butana,and Bashaiyer were stable over all environments, while the genotypes W-Ahmed,Tabat, Mugod, and Safra were adapted for specific environments. W-Ahmed and Tabat for favorable environment, while Mugod and Safra were adapted for specific environment (South Gedarif environments). Genotype Mugod exhibited high yield in the environment 6 which represent South Gedarif environment,followed by the genotypes Gadambalia bloom,Safra, and genotype Tetron, respectively. (Fig 1).

To further explain the GE and stability,a bi-plot between the PCA1 and PCA2 scores were given in Fig2. AMMI bi-plot of the first two principle component axes is a powerful way of detecting important score of GE effects (Zobel *et al*.1988).This analysis represents stability of the genotypes across environments in terms of principle component analysis. It is used to identify broadly adapted genotypes that offer stable performance across sites, as well as genotypes that perform well under specific conditions. In this study, the first two principal component axes (PCA1 and PCA2) in bi-plot analysis explained a large proportion of the variation 76% of the total GE sum of squares (Table 3).On this AMMI bi-plot ,genotypes and environment having PCA values close to zero (near the origin) have small interaction effects, whereas those having large positive or negative PCA values (distant from zero) largely contribute to GE interaction (Yau,1995). Hence, the genotypes Butana, Farhoda, Faki-Mustahi, ashaiyer, Gadambalia bloom, Safra, and Wad baku were the most interactive ,while the genotypes W-Ahmed, Tabat, Wad Fahal,and Gesheish were the least interactive. On the other hand, environments E-9 and E-6 appeared we distant from the origin (large PCA score), hence they had large interaction effects, whereas E-2 had small interaction effects (Fig.2). Genotypes Tabat,W-Ahmed, and Wad Fahal were more stable and responsive for good environments (Rahad environment),while the genotypes Mugod, Tabat ,Wad-Ahmed, Safra, and Tetron were responsive and suitable for South Gedarif environment. Hence, in this investigation, visual observations of AMMI bi-plot analysis enable the identification of genotypes and testing environments that exhibited major sources of GE interaction as well as those that were stable. Similar results were reported by Sneller *et al* (1997). From the result shown in Table 4 and Fig 2, it was found that the genotypes Mugod, Wad-Ahmed, Tabat, Gadambalia bloom, Safra and Tetron were high yielding and stable under favorable environments, and they could be grown under high rainfall and Rahad conditions. The others (Wad Baku, Farhoda, Gesheish and Wad Fahal) were quite stable under unfavorable conditions, and it could be grown under low rainfall conditions of North Gedarif. In this study, comparing the effectiveness of joint regression and AMMI analysis for analyzing GE interaction, it was found that PCA1 in AMMI accounted for the GE sum of squares by 56.7%, while regression analysis accounted forGE sum of squares by 21.9%. Hence, AMMI analysis was superior to regression techniques in accounting for GE sum of squares and more effective in partitioning the interaction sum of squares.

From these two models of stability used in this study, it was found that the genotypes Mugod, Wad-Ahmed, Tabat, Gadambalia bloom, Safra and Tetron were high yielding and stable under favorable environment, and could be grown under high rainfall and Rahad conditions, others (Wad Baku, Farhoda, Gesheish and Wad Fahal) were quite stable under unfavorable conditions, and could be grown under low rainfall conditions of North Gedarif.

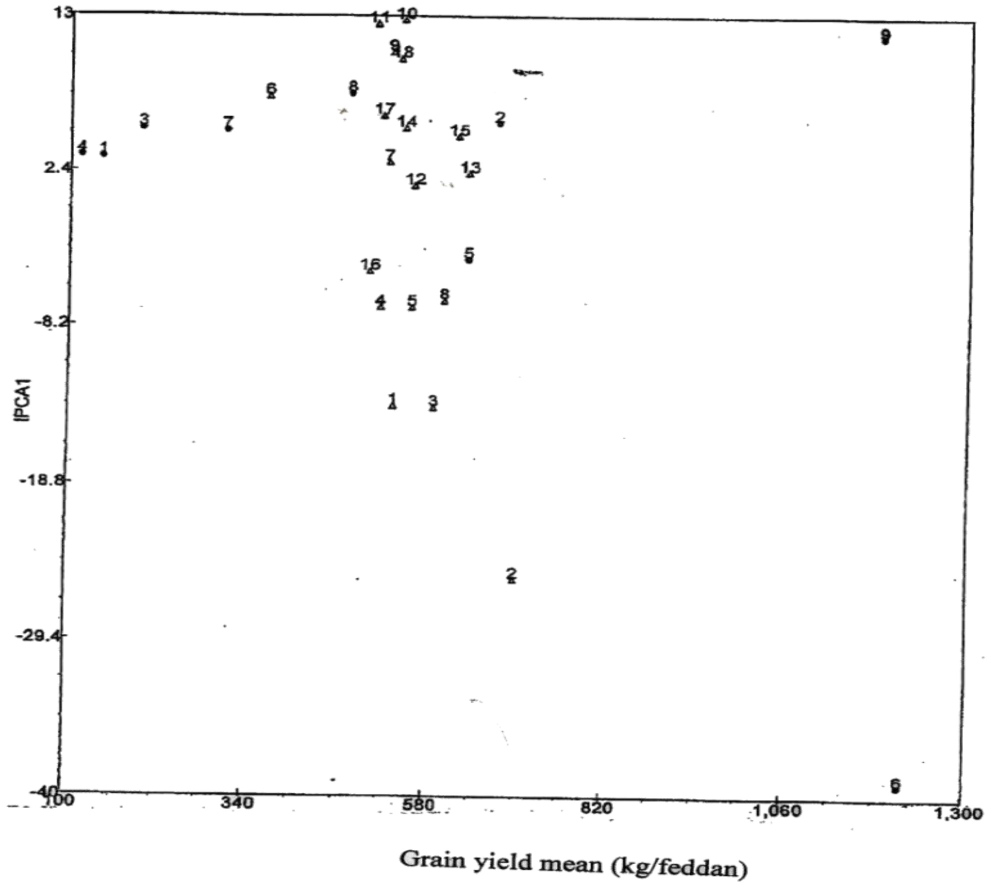

Fig.1. The AMMI biplot of the main and the PCA1 effects of both genotypes and environments on grain yield of 18 sorghum genotypes grown in nine environments. Genotypes are indicated by triangles while environments are represented by circles.

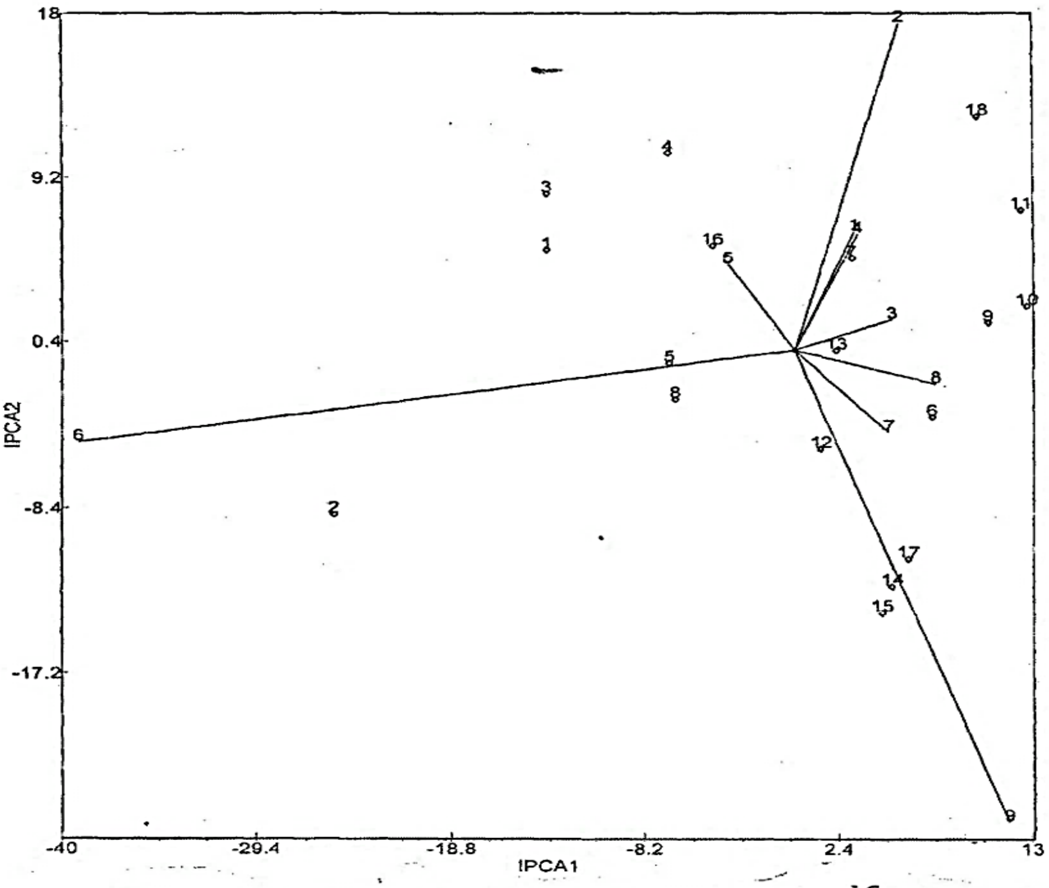

Fig.2.The AMMI biplot of the PCA1 and PCA2 axes for grain yield of 18 sorghum genotypes grown in nine environments.Genotypes are indicated by triangle while environments are represented by circles.

CONCLUSION

Based on the results of this study, it could be concluded that the genotypes Mugod,Tabat, Wad-Ahmed, Gadambalia bloom, Safra and Tetron were high yielding and stable under favorable environment, and could be grown under high rainfall and Rahad irrigation conditions. Genotypes Wad Baku, Farhoda, Gesheish and Wad Fahal were quite stable under unfavorable conditions, and could be grown under low rainfall conditions of North Gedarif. Further testing of the unsuitable genotypes is necessary for further breeding manipulations. Both parametric and non- parametric approaches of stability analysis (Eberhart and Russell as well as AMMI) agreed in identifying stable genotypes over different environments**.**

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تحليل التفاعل الوراثي – البيئي وثبات درجة إنتاجية الحبوب في الذرة الرفيعة
[*Sorghum bicolor* (L .) Moench] تحت ظروف الأمطار والري في السودان

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[2] كلية العلوم الزراعية ، جامعة الجزيرة ، وادمدني ، السودان .

الخلاصة

أجريت هذه التجربة لثلاث مواسم متتالية (2009 ، 2010 و 2011) وفي ثلاثة مواقع هي مزرعة بحوث الرهد ومحطة بحوث القضارف (منطقة شمال وجنوب القضارف) ،هيئة البحوث الزراعية، السودان، واللتان تمت فيهما الزراعة بالأمطار ، أما محطة الرهد بالري الانسيابي. استخدم تصميم القطاعات العشوائية الكاملة بأربعه مكررات. وجد أن البيئة لها تأثير كبير علي انتاجية الذرة الرفيعة في مناطق زراعتها وعلية فأن التفاعل الوراثي والبيئي عالي المعنوية في حالة التربية لبيئات محددة. هدفت الدراسة لتقويم التفاعل الوراثي والبيئي وثبات درجة انتاجية الحبوب في الذرة. أظهرت النتائج وجود فروق معنوية عالية للبيئات ,الأصناف والتفاعل الوراثي والبيئي. أيضاً أظهرت الدراسة فروقات معنوية عالية لمعظم الصفات التي درست في كل المواسم ، وهذا يشير الى وجود فروقات عالية بين سلالات الذرة للصفات التي درست ، وعليه يمكنها الاستجابة للانتخاب . التفاعل الوراثي والبيئي به فروق معنوية لمعظم الصفات وهذا يوضح أن هذه السلالات تختلف في استجابتها باختلاف البيئات وبعضها في بيئات محددة. مقارنة فعالية طريقة تحليل معامل الارتداد الخطي وطريقة الاثر التجميعي الرئيسي والتفاعل المتراكم لتحليل اثر التفاعل بين الصنف والبيئة اوضحت الدراسة ان محور المكون الاول والثاني في طريقة الاثر التجميعي الرئيسي والتفاعل المتراكم فسر 21,9 % من قيمة تفاعل البيئة مع التركيب الوراثي اما معامل الارتداد قد فسر حوالي 19,3%،56,7% من قيمة التفاعل بين البيئة والتركيب الوراثي وعليه ، طريقة الاثر التجميعي الرئيسي والتفاعل المتراكم تفوقت علي طريقة تحليل معامل الارتداد الخطي وهي ذات كفاءة عالية في تقسيم مجموع مربعات الانحرافات. بناءً علي نماذج التحليل (Eberhard and Russel و1966 (Additive Main Effects and Multiplicative Interaction) AMMI) لتحديد ثبات الاداء معاً وجد أن السلالات ذات الإنتاجية العالية هي مقد(1510 كجم/ هكتار) ، طابت (1299 كجم/هكتار)، ود أحمد (1471 كجم/ هكتار) ، زهرة القدمبلية 1323 كجم/هكتار) وتيترون(1410 كجم/هكتار) ، صفراء(1428 كجم/هكتار) ذات انتاجية عالية وثابتة ويمكن زراعتها في جنوب القضارف والرهد والسلالات ود باكو(1225 كجم/هكتار) ، فرهوده (1230 كجم/هكتار) وود فحل (1194كجم/هكتار)، قشيش (1252 كجم/ هكتار) ذات انتاجية أقل ولكنها ثابتة نسبياً ويمكن زراعتها في شمال القضارف.