GGE BIPELOT ANALYSIS FOR YIELD PERFORMANCE OF GRAIN AMARANTH GENOTYPES ACROSS DIFFERENT ENVIRONMENTS IN WESTERN INDIA

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ABSTRACT

Stable performance of grain amaranths genotypes at specific environment is critical for obtaining high and consistent yield. This study was conducted to assess grain yield stability of thirteen genotypes in varied environments in three successive growing seasons and effects of genotype (G) and genotype×environment (GE) interaction were illustrate graphically based on “what-won-where” to advocate genotypes for a specific environment, using GGE biplot. Result of study revealed that GGE biplot was effective to recognize stable and highest yield (1648.92 kg/ha) genotype as G\textsubscript{5} followed by G\textsubscript{6} (1457.24 kg/ha) and G\textsubscript{3} (1268.62 kg/ha) genotypes while the genotype G\textsubscript{7} had the lowest grain yield and was the least stable across varying environments. This study could be aid tool for endorsement of amaranths genotypes for specific environment, taking into elucidation the peculiarities of genotypes and growing stipulation.

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1 Introduction

Grain amaranth belong to the genus *Amaranthus* is one of the astounding underutilized pseudocereal with rich nutritional diet profile and seldom utilized as used as food grain, leafy vegetables, forage and ornamentals for long. It includes approximately 60 species (Sauer, 1967), of them five major species considered for grain production of grain type *Amaranthus* *vitis*, *A. hypochondriacus* L. (2n=32), *A. cruentus* (2n=34), *A. caudatus* L. (2n=32 and occasionally 2n=34 also), *A. adalis* Spegazzini (2n=32) and *A. tricolor* (2n=34) (Patel et al., 2014). Grain amaranths is rich in "Protein complements" with higher lysine content than other cereal grains which offers remarkable opportunity to exploit grain amaranth (Bressani, 1989). It has been well reported that amaranth leaves are excellent sources of protein, with its maximum accumulation in the blossoming phase (Kadoshnikov et al., 2005). Therefore, it is a good diet supplement to pulses for sulphur rich amino acid. Crop is widely spread over Asia with astounding genetic and morphological diversity and nutritional pool, nevertheless crop breeding program have given little attention over genetic improvement of this "alternative crop". The aptness to develop prominent high yielder and stable genotypes over wide environment is an unambiguous motto in pragmatic plant breeding programme (Boshev et al., 2014). Assorted environments can diminish the steadiness of plant varieties (Hebert et al., 1995). Genotype × environment interaction (GE) have shown there supremeness for delineating stability of genotypes and have partitioned variation that better aid for selection of consistent stable genotypes in many different studies (Dehghani et al., 2006; Yan et al., 2007; Sabaghnia & Sabaghpour, 2008). There are several methods for stability analysis among which GGE biplot analysis was used in the present study to deduce stability of the crop with aim to investigate the stability of seed yield in amaranths and graphically summarize and considerate the assets of G and GE interaction (Yan & Kang, 2003; Samonte et al., 2005; Dehghani et al., 2009; Balestre et al., 2009; Oliveira et al., 2010; Tonk et al., 2011). Present study was undertaken for the first time to gather information about GE interaction of different amaranth genotypes for high seed yield using three year data using GGE biplot analysis.

2 Materials And Methods

2.1 Experimental site and materials

The experiment was carried out at the Crop Improvement Research Station (24°12’ N, 72°12’ E and 154.5 m), Sardarkrushinagar Dantiwada Agricultural University, Sardarkrushinagar, Gujarat, India. Thirteen genotypes *vitis*, Annupurna, Durga, BGA-2, GA-1, GA-2, GA-3, PRA-1, PRA-2, PRA-3, RMA-4, RMA-7, Suvarna and VL-344 from diverse backgrounds were sown in randomized block design (RBD) design with three replications in six rows of 4 meter length with 45 × 15 cm spacing for each genotype. All the genotypes were grown during the *Rabi* season in 2012-13, 2013-14 and 2014-15 to access their stability for grain yield across variable environments. The size of unit plot was 4.0 × 1.8 msq. Plots were thinned duly ensuring a single plant per hill. Two rows of each plot were harvested at maturity, silique were shelled, dried out and grain yield was measured in each plot.

2.2 Statistical analysis

Statistical computations and estimations were carried out using INDOSTAT software. Analysis of variance was carried out to partition the variation due to genotypes, environment and GE interaction. Stability analysis of data was carried out by employing Eberhart & Russell model (1966). The untransformed data of each genotype from field trials were subjected to G × E biplot analysis for deduction of GE interaction using PBTools software version 1.4 (PBTools, 2014). The GGE biplot is a multi-faceted most comprehensive tool and produce lucrative informative graphs depicting (i) "what-won-where" pattern, (ii) ranking of amaranth genotypes with respect to yield and stability, (iii) environment vectors, and (iv) assessment of environment to ideal environment (Yan & Kang, 2003). The GGE biplot study execute by using singular value decomposition (SVD) model that presents the first two principal components (PC1 and PC2, referred as primary and secondary effects, respectively) resulting from environment centered yield data (yield discrepancy due to GGE) based on symmetric scaling f=0.5 (Yan et al., 2000). Each environment is characterized by its vector (the line that connects it with the origin of the biplot), the length of the vector was used to determine the discriminating ability of each of the test environments, with a shorter vector implying that the environment was not well represented by PC1 and PC2 (Yan et al., 2007). The angle between environments vectors were used to judge correlations (similarities/dissimilarities) between pairs of environments (Yan & Kang, 2002).

3 Results and Discussion

Development of a stable variety is one of the major goals for all breeding programme because phenotypically stable genotypes are usually required for commercial production of crop plants. Hence, to find out stable genotypes for different characters, stability analysis was employed as suggested by Eberhart & Russell (1966) was employed. Accordingly, three kinds of linear responses (bi) *vitr.,* bi<1, bi=1 and bi>1 have been considered in which bi=1 is average stability and widely adaptable to different environments; bi>1 is below average stability, increasing sensitivity to environmental changes and well adapted to favourable environment and bi<1, above average stability, greater tolerance to environmental changes; thereby genotypes would have the specific adaptability to poor yielding environment.

Based on ANOVA it was concluded that all the thirteen amaranth genotypes significantly differed from each other indicating the presence of substantial variation among them (Table 1). Further, the performance of all the genotypes varied under all the environments and it is depicted in figure 1. Based on mean yield data, each genotype was ranked which is given in table 2.
The set of thirteen genotypes was evaluated under three environments. The data of analysis of variance for different characters are presented in table 1. The G × E interaction was found significant for all the characters except for inflorescence length, which revealed that genotypes interacted differently with environmental variations for days to flowering, days to maturity, plant height, test weight, inflorescence length, plant stand at harvesting, fodder yield and grain yield characters. The variances due to G × E were further partitioned into components, (i) G × E (linear) and (ii) G × E (non-linear) i.e., pooled deviation. Pooled deviation, the non-linear component of G × E interaction was observed significant for the traits, days to flowering, days to maturity, plant height, test weight, inflorescence length and grain yield, whereas plant stand at harvesting and fodder yield were

Table 1 Analysis of variance (mean squares) for stability pertaining to various characters in amaranth genotypes

| Source of variation | Degree of Freedom | Days to flowering | Days to maturity | Plant height | Test Weight (10ml/g) | Inflorescence Length (cm) | Plant stand at harvesting | Fodder yield (kg/plot) | Grain yield (kg/plot) |
|---------------------|-------------------|-------------------|-----------------|-------------|---------------------|---------------------------|--------------------------|----------------------|----------------------|
| Genotypes (G)       | 12                | 432.66**          | 238.22**        | 3,756.04**  | 0.01                | 418.64**                  | 143.90                   | 3,770,923**          | 165,246**           |
| Environments (E)    | 2                 | 555.52**          | 248.23**        | 6,239.14**  | 0.39**              | 2101.35**                 | 4177.14**               | 229,989,508**        | 3,152,549**         |
| G x E               | 24                | 8.66*             | 7.20*           | 122.72**    | 0.01*               | 81.03                     | 123.15**                 | 1,335,427**          | 334,988**           |
| Environment (Linear)| 1                 | 1111.05**         | 496.45**        | 12,478.29** | 0.77                | 4202.69**                 | 8354.28**               | 459,979,017**        | 6,305,098**         |
| G x E (Linear)      | 12                | 15.81**           | 11.23**         | 154.31      | 0.01**              | 145.60**                  | 245.20**                 | 2,348,038**          | 34,541*             |
| Pooled deviation    | 13                | 1.40**            | 2.92*           | 84.12**     | 0.01**              | 15.20**                   | 1.01                     | 297,984**            | 30,863*             |
| Pooled error        | 72                | 1.32              | 1.08            | 11.42       | 0.01                | 6.89                      | 160.66                   | 686,233              | 48,935               |

*, ** Significance at 5 and 1 per cent probability levels, respectively

Table 2 Mean grain yield (Kg/ha) of thirteen amaranth genotypes across three environments at E₁, E₂ and E₃ their average seed yield

| Name of genotype | Genotype code | E1     | E2     | E3     | Average grain yield (Kg/ha) | Rank |
|------------------|---------------|--------|--------|--------|----------------------------|------|
| Annpurna         | G1            | 658.40 | 902.72 | 1212.04| 924.39                     | 12   |
| Durga            | G2            | 1078.13| 1120.30| 2148.77| 1449.07                    | 3    |
| BGA-2            | G3            | 710.25 | 1023.08| 2072.53| 1268.62                    | 5    |
| GA-1             | G4            | 1382.64| 944.38 | 1736.73| 1354.58                    | 4    |
| GA-2             | G5            | 1351.78| 1347.14| 2247.84| 1648.92                    | 1    |
| GA-3             | G6            | 1189.24| 1182.79| 1999.69| 1457.24                    | 2    |
| PRA-1            | G7            | 754.28 | 490.71 | 1390.43| 878.47                     | 13   |
| PRA-2            | G8            | 588.45 | 773.10 | 1477.78| 946.44                     | 11   |
| PRA-3            | G9            | 711.90 | 892.54 | 1507.72| 1037.39                    | 10   |
| RMA-4            | G10           | 684.32 | 923.55 | 1549.69| 1052.52                    | 9    |
| RMA-7            | G11           | 537.83 | 1138.82| 1918.83| 1198.49                    | 7    |
| Suvarna          | G12           | 563.34 | 969.85 | 1758.95| 1097.38                    | 8    |
| VL-344           | G13           | 771.56 | 1064.75| 1836.11| 1224.14                    | 6    |
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unpredictable due to non significant of pooled deviation as well as lower magnitude than linear component. The non-linear effect must be significant and of lower magnitude than linear component to predict the performance of genotype and its stability. This reflected greater importance of linear portion in building up total G × E and the possibility of prediction across the environments for these characters. The seasonal variation in these characters may be due to micro-environmental conditions i.e., differences in climatic or soil factors among environments, during the grain filling stage. The variation in meteorological parameters viz., temperature (ºC) and relative humidity (%) are represented in figure 2. The genotypes x environment interaction was highly significant for mean grain yield, which revealed that genotypes interacted differently with environmental variations in character.

On analyzing SVD based GGE biplot analysis, the GGE biplot revealed that component PC1=73.6% and PC2=21.5% explaining total 85 percent of environmental centred variation of mean grain yield. The observed high magnitude of G×E (linear) component could lead to the identification of genotypes adapted to different environmental conditions on the basis of deviation from the regression line of unit slope (Figure 3).

3.1 What-won-where Biplot for vertex/ideal genotype

The biplot (Figure 3) represents a polygon, where some of the genotypes were placed on the crests, while the rest were surrounded by the polygon. As the genotypes placed on the peak had the longest detachment from the biplot origin and they were expected to be the most responsive. The genotypes at the crests of the polygon could be called the vertex/ideal genotype.

In present study, the genotypes G 4 in E 1 are the vertex genotype, which had the highest grain yield. The two environments (E 2 and E 3) were to be found in the same sector on the graph, which recommended that these environments did not differ significantly among themselves. The genotype G i is the only apex genotype for environment E i and E j environments. None of the environments fell in the sectors with genotypes, G 1, G 2, G 3 and G 11, representing that these genotypes were not appropriate for growing in these environments.

In an “ideal” view (Figure 4), it was observed that the genotype G 5 (1648.92) was in close proximity to the ideal genotype, followed by G 6 (1457.24 Kg/ha) and G 4 (1354.58 Kg/ha), respectively. According to Yan & Kang (2003), a model genotype could be described as one which was the uppermost yielding across tested environments and is utterly stable in its performance.

3.2 Average yield and stability of genotypes

The average grain yield and stability of the genotypes presented in Figure 4. The AEAaxis (average environmental axis, AEA) passes across the biplot origin. The point of average environment coordinates for environments was indicated by open blue circle with an arrow. An “ideal” genotype was represented by closed blue dot in Figure 4. The higher yielding genotypes located closer to the circle; the stable genotypes are lie on the upper area of the line, and unstable are those in the lower fraction of the biplot. Considering

Figure 2 Meteorological parameters of three environments (RH-1: Relative Humidity at 0700 LMT, RH-2: Relative Humidity at 0700 LMT, Av. RH: Average Relative Humidity, T max: Maximum Temperature, T min: Minimum Temperature, T mean: Average Temperature)
Figure 3 A genotype + (genotype × environment) interaction biplot showing genotype performance in each environment.

Figure 4 Comparison of genotypes with the ideal genotype showing the environmental axis (AEA) the GGE biplot. Environments and genotypes are denoted by 'E' and 'G', respectively. AXIS1 and AXIS2 are the first and second principal components, respectively.
this, the highest projection on the performance line holding by
genotype G5 has the highest average grain yield (1648.92 Kg/ha),
followed by G6 (1457.24 Kg/ha) and G4 (1354.58 Kg/ha) which are
positioned very close to the genotype G5 (Figure 4).

3.3 Environment evaluation based on GGE biplot

The cosines of the angle between parents were used for the
analysis of the interrelationship between entries / testers:
\[
\cos \alpha_{ij} = r_{ij},
\]

Where, \( \alpha_{ij} \) is the angle between environments \( i \) and environments \( j \)
and \( r_{ij} \) is the correlation coefficient between both the environments.

If the angle between their vectors is \(<90^\circ\) considering the two
environments are positively correlated, if the angle is \(>90^\circ\) they are
negatively correlated, and independent if the angle between them is
90°. The angle of 0° specifies that the correlation \( [r] \) is 1 and the
angle of 180° represents that the correlation is −1. The more
discriminating entries exist testers with longer vectors, while less
discriminating has short vectors and those position at the biplot
origin are not discriminating Rastogi et al. (2011).

The environments were presented in Figure 5 has discriminating
ability and representativeness. The representative environment of
all other environments has longest distance between the marker of
the environment to the biplot origin, is a measure of its
discriminating ability considered as ideal environment, that is most
discriminating for genotypes and shortest projection from the
marker of location onto the AEA Y-axis is the measurement of its
representativeness (Yan, 2001; Yan & Kang, 2003).

Considering this, E3, as it is, as E3 is far away from the plot origin
and had the shortest projection onto AEA Y-axis was the most
discriminating as well as the most typical environment,
respectively. The other favorable environment E2 was positioned
close to E3, which indicates that stable production of amaranths is
possible in this environment. The pattern of environments on the
biplots suggested that all the environments were positioned in
different concentric circle (Figure 5). In present study, as the angle
between E2 and E3 environments was less than 90°, it revealed that
G × E was moderately small and these environments tend to
discriminate among genotypes in a similar manner and have a
strong relationship. Corresponding environments were considered
as the best environments for genetic discrepancy of genotypes
under study (Tonk et al., 2011; Miah et al., 2015). Besides, the
environment which is not far away from the origin of biplot did not
have the discriminating ability and was not illustrative (E1), as the
AEA Y-axis shown large projection (Figure 5).

Figure 5 Comparison of environments with an ideal environment. The genotypes and environments are indicated by G and E,
respectively.
3.4 Relationship among the environments

The correlation between the test environments is represented by the vectors of all three environments that facilitate the determination of the relationship between environments (Figure 6). In biplot environment view, the vectors of three environments depict the relationship between environments while cosine of the angle between two environments shows the relationship among them (Yan, 2001). Both, E1 and E3 had the longer vectors thus, they were the best for genetic discrimination of genotypes but on considering the angle between these two environments they are comparatively less discriminating than E2. The environment E2 was the least representative environment in this investigation because it has a shorter vector. Minimum angle between the vectors of E1 and E2 has shown that they had robust correlation.

An essential target in a breeding program is to accommodate authentic indication that will gratify as a guide for selection of the best genotypes that have to be planted in the following seasons and to be capable to forecast yield as exactly as possible based on limited experimental data. The objective of any breeding experiment is to put up authentic clue that will gratify as a guide for selection of the model genotypes and ability for projection of yield as exactly as likely based on restricted experimental data. The amaranth genotypes effectively identified by means of GGE biplot which should be considered for growing in E2. Moreover, by means of this method, it was apparently established that high and stable yields could be attained only in specific environment. Other researchers observed that GGE biplot analysis is a suitable device for detecting experimental environments to select best genotypes in field crops as well (Balestre et al., 2009; Ilker et al., 2009; Oliveira et al., 2010; Tonk et al., 2011; Khalil et al., 2011; Beyene et al., 2011, Nzuve et al., 2013; Mortazavian et al., 2014; Miah et al., 2015).

Conclusion

In the present study, the genotypes G4 was the vertex genotype in E1 whereas, G5 was vertex genotype in E2 and E3, with the highest seed yield. From “ideal” view it was reported that genotype G5 was the next to the ideal genotype, followed by G6 and G3, respectively. With regard to the environments, E3 was the most discriminating as well as the most typical environment. The stable production of amaranths is possible in favorable environment E2 as it was positioned close to E3. Hence, it was concluded that GGE biplot could be efficiently used to predict stable and high yielding genotypes as well as best performing environments for the cultivation of amaranth.

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Figure 6A genotype + G × E interaction biplot showing relationships among three environments.
Conflict of interest
Authors would hereby like to declare that there is no conflict of interests that could possibly arise.

References

Balestre M, Souza JC, Pinho RGV, Oliveira RL, Paes JMV (2009) Yield stability and adaptability of maize hybrids based on GGE biplot analysis characteristics. Crop Breeding and Applied Biotechnology 9: 219-228.

Beyene Y, Mugo S, Mutinda C, Tefera T, Karaya H, Ajanga S, Shuma J, Tende R, Kega V (2011) Genotype by environment interactions and yield stability of stem borer resistant maize hybrids in Kenya. African Journal of Biotechnology 10: 4752-4758.

Boshev D, Jankulovska M, Ivanovska S, Jankuloski IL, KuzManovska B, Tanaskovic V (2014) Evaluation of maize hybrids for grain yield stability under rainfed and irrigated conditions using GGE biplot analysis. Bulgarian Journal of Agricultural Science 20: 1320-1325. DOI: 10.4236/ajps.2014.511180

Bressani R (1989) The proteins of grain amaranth. Food Reviews International 5: 13-38.

Dehghani H, Ebadi A, Yousefi A (2006) Biplot analysis of genotype by environment interaction for barley yield in Iran. Agronomy Journal 98: 388-393. DOI: 10.2134/agronj2004.0310

Dehghani H, Sabaghnia N, Moghaddam M (2009) Interpretation of genotype by environment interaction for late maize hybrids’ grain yield using a biplot method. Turkish Journal of Agriculture and Forestry 33: 139-148. DOI:10.3906/tar-0712-25

Eberhart SA, Russell WL (1966) Stability parameters for comparing varieties. Crop Science 6: 36-40. DOI:10.2135/cropsci1966.0011183X000600010011x

Hebert Y, Plomion C, Harzic N (1995) Genotypic × environment interaction for root traits in maize as analysed with factorial regression models. Euphytica 81: 85-92.

Ilker E, Tonk FA, Caylak O, Tosun M, Ozmen I (2009) Assessment of genotype × environment interactions for grain yield in maize hybrids using AMMI and GGE biplot analyses. Turkish Journal of Field Crops 14: 123-135.

Kadoshnikov SI, Serge I, Kadoshnikova, IG, Martirosyan DM (2005) Investigation of fractional composition of the protein in amaranth. In: Non-traditional natural resources, innovation technologies and products, Russian Academy of Natural Sciences, Moscow, Pp. 81-104.

Khalil IA, Rahman H, Rehman NU, Arif M, Khalil IH, Iqbal M, Ullah H, Afridi K, Sajjad M, Ishaq M (2011) Evaluation of maize hybrids for grain yield stability in North West of Pakistan. Sarhad Journal Agriculture 27: 213-218.

Miah MA, Rasul MG, Mian MAK, Rohman MM (2015) Evaluation of rapeseed lines for seed yield stability. International Journal of Agronomy and Agricultural Research 7: 12-19.

Mortazavian SMM, Nikkah HR, Hassani FA, Sharif-al-Hosseini M, Taheri M, Mahlooji M (2014) GGE Biplot and AMMI analysis of yield performance of barley genotypes across different environments in Iran. Journal of Agricultural Science and Technology 16: 609-622.

Nzuve F, Githiri S, Mukunya DM, Gethi J (2013) Analysis of genotype × environment interaction for grain yield in maize hybrids. Journal of Agricultural Science 5: 75-85. DOI: http://dx.doi.org/10.5539/jas.v5n1l75

Oliveira RL, Garcia R, Von Pinho RG, Balestre M, Ferreira DV (2010) Evaluation of maize hybrids and environmental stratification by the methods AMMI and GGE biplot. Crop Breeding and Applied Biotechnology10: 247-253. DOI: http://dx.doi.org/10.1590/S1984-70332010000300010

Patel KS, Parihar A, Chaurasia P, Patel PJ, Pachchigar K (2014) Molecular characterization in grain amaranthus (Amaranthus spp.) using RAPD marker. Research Journal of Biotechnology 9: 29-35.

PB Tools, version 1.4. (2014) Biometrics and Breeding Informatics, PBGB Division, International Rice Research Institute. Los Baños, Laguna.

Rastogi A, Mishra BK, Srivastava M, Siddiqui A, Shukla S (2011) Biplot approach for identification of heterotic crosses in linseed (Linum usitatissimum L.).Journal of Botany Pp. 1-7.DOI: http://dx.doi.org/10.1155/2011/353102

Sabaghnia DNH, Sabaghpour SH (2008) Graphic analysis of genotype × environment interaction of lentil yield in Iran. Agronomy Journal 100: 760-764.

Samonte SOP, Wilson LT, Mc Clung AM, Medley JC (2005) Targeting cultivars onto rice growing environments using AMMI and SREG GGE biplot analysis. Crop Science 45: 2414-2424. DOI:10.2134/agronj2006.0282

Sauer JD (1967) The grain amaranths and their relatives: a revised taxonomic and geographic survey. Annals of the Missouri Botanical Garden 54: 103-137.DOI: 10.2307/2394998

Tonk FA, Ilker E, Tosun M (2011) Evaluation of genotype × environment interactions in maize hybrids using GGE biplot analysis. Crop Breeding and Applied Biotechnology11: 1-9.Doi:10.1590/S1984-70332011000100001

Yan W (2001) GGE biplot-A windows application for graphical analysis of multi-environment trial data and other types of two-
way data. Agronomy Journal 93: 1111-1118. doi:10.2134/agronj2001.9351111x

Yan W, Hunt L.A, Sheng Q, Szlavnics Z (2000) Cultivar evaluation and mega-environment investigation based on the GGE biplot. Crop Science 40: 597-605. doi:10.2135/cropsci2000.403597x

Yan W, Kang MS (2002) GGE biplot analysis: A graphical tool for breeders, geneticists, and agronomists. CRC Press. Yan W, Kang MS (2003) GGE biplot analysis: a graphical tool for breeders, geneticists and agronomists. CRC Press, Boca Raton, FL.

Yan W, Kang MS, Ma B, Woods S, Cornelius PL (2007) GGE biplot vs. AMMI analysis of genotype by environment data. Crop Science 47: 643-655. doi:10.2135/cropsci2006.06.0374