Comparison and suitability of genotype by environment analysis methods for yield-related traits of pearl millet

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Abstract
Pearl millet (Pennisetum glaucum (L.) R. Br.) is an important food security and income crop for households living in semi-arid zones in Uganda. However, the genotype by environment interaction, in addition to the several methods used for its assessment, complicates selection of varieties adapted to such semi-arid areas. The objective of this study, therefore, was to compare common methods used to assess stability and adaptability of improved genotypes. Seventy six genotypes were planted in four environments in an alpha experimental design with two replications. Results showed that genotype by environment interactions were significant at p<0.05 for grain yield, days to 50% flowering and 50% physiological maturity, percentage of productive tillers and panicle area. Results further showed inconsistency in ranking of genotypes between methods; although Cultivar Superiority, REML, Yield Stability Index and GGE biplot were consistently correlated and identified high yielding and stable genotypes.

Key words: GGE biplot, grain yield, pearl millet, stability analysis, Uganda

Introduction
Pearl millet (Pennisetum glaucum (L.) R. Br.) is one of the widely grown millets with several food and non-food uses (IFAD, 1999). The crop responds positively to adverse environments that are extremely variable and often associated with erratic and low annual rainfall (Bashir et al., 2014). Despite the adaptability, average productivity of about 600 kg ha⁻¹ (Rai et al., 1999) from farmers’ fields is low much as relatively high yielding genotypes adapted to low-input and drought-prone environments have been developed (Serraj et al., 2003; Vadez et al., 2012). This is partly because the potential performance of the high-yielding genotypes under marginalised conditions is always obscured by the multiplicative effect of genotype by environment interaction (GEI) (Yan and Racjan, 2002).

http://dx.doi.org/10.4314/ujas.v17i1.6
Accordingly, this causes inconsistent performance of genotypes (Alberts, 2004), and thus leading to false selection (Crossa, 1990; Falconer, 1990).

It is in response to these challenges that it is necessary to assess genotypes for adaptability and stability (Becker and Léon, 1988). Equally important is the need to develop appropriate statistical models that have the rigor and accuracy to support selection decisions in case significant GEI exists, and hence identification of a reliable method is important (Yau, 1991).

Several statistical analysis methods have been developed to assess GEI, notable of which are: analysis of variance (ANOVA), environmental variance ($S_i^2$), deviation from regression ($S_d^2$), Restricted Maximum Likelihood (REML) (Bartlett, 1937), regression coefficient ($b$) (Finlay and Wilkinson, 1963), Wricke’s ecovalence ($W_i$), Eberhart and Russell (1966), Best Linear Unbiased Predictions (BLUP) (Patterson and Thompson, 1971), Tai’s (1971) approach, Shukla stability variance ($\sigma^2$) (Shukla, 1972), coefficient of determination ($r^2$) (Pinthus, 1973), coefficient of variation (CV) (Francis and Kannenberg, 1978), cultivar superiority ($P_i$) (Lin and Binns, 1988) and static stability (Becker and Léon, 1988). Some of the most frequently used methods include; Additive Main Effects and Multiplicative Interaction (AMMI) (Gauch, 1988), yield stability index (YSi) (Kang, 1993), AMMI stability value (ASVi) (Purchase, 2000), Genotype and Genotype by Environment (GGE) biplot (Yan and Hunt, 2002) and harmonic mean of the relative performance of genotypic values (MHPRVG) (Resende, 2007). However, most of the methods have deficiencies.

The ANOVA identifies sources of variation due to GEI effect and allows for estimation of variance components used to calculate trait heritability. However, it does not explore the underlying structure within the GEI; making it difficult to establish the true performance of genotypes across environments (Crossa, 1990). The regression approach is widely used (Westcott, 1986; Freeman and Perkins, 1971) but limited in functionality because genotype response to environments is largely under multivariate control; yet regression transforms it into a univariate variable (Lin et al., 1986). Crossa (1990) also noted that parameters of regression (mean, slope, and deviation) also make it difficult to identify superior genotypes for particular environments. The YSi has a weakness of weighing strongly on yield, yet the trait is influenced by many factors (Farshadfar et al., 2011). Wricke’s partition of the interaction is non-orthogonal yet the test is parametric (Freeman and Perkins, 1971). The AMMI models (Gauch, 2006; Gauch et al., 2008) combine the ANOVA for the genotype and environment main effects with principal components analysis which helps to obtain further insight into the nature and extent of complex GEI (Alberts, 2004; Gruneberg et al., 2005). However, there is difficulty in interpretation of the interaction when there is limited variability accounted for by the first principal component, which could indicate false statistical stability of the genotypes and environments (Lavoranti et al., 2007). The AMMI and the GGE biplot combine genotype (G) and genotype by environment (GE) biplot (Yan and Hunt, 2002) and harmonic mean of the relative performance of genotypic values (MHPRVG) (Resende, 2007). However, most of the methods have deficiencies.
probably no stand-alone method exists (Kaya et al., 2006). Thus the objective was to assess stability analysis methods for correlation and consistency using traits of improved pearl millet genotypes.

Materials and methods

Test environments and materials

The study was conducted for two rainy seasons which coincided with the second rains of 2012 and first rains of 2013. The evaluation was done in two locations (Kitgum and Serere) and this resulted in four environments. The Kitgum environments (E1 and E2) are located at 03°13′N, 032°47′E, 969 m.a.s.l while the Serere (E3 and E4) environments are located at 01°32′N, 033°27′E, 1140 m.a.s.l. E1 received 391 mm of rainfall in 2012; while E2 received 817 mm of rainfall in 2013. E3 received 499.3 mm of rainfall in 2012; while E4 received 589 mm of rainfall in 2013. The environments were characterised as hot spots for rust disease (Lubadde et al., 2014), sandy soils and being semi-arid.

The 76 improved pearl millet genotypes evaluated were replicated twice in a 4 x 19 alpha experimental design. The materials were planted in 8 m x 5 m plots at a spacing of 60 cm x 30 cm. A soil fertility regime recommended for seed production under rain fed conditions was adopted and standard agronomic practices for crop management were used (Khairwal et al., 2007).

Data collection and analysis

Data were collected on at least 36 randomly selected plants per plot, using the ‘Descriptors of Pearl Millet’ (IBPGR and ICRISAT, 1993). The panicle area (PAR) was calculated as 3.14 x L x W; where L and W were panicle length and width, respectively. Data were also collected on: grain yield (GY in kg ha⁻¹) at 50% physiological maturity after threshing, days to 50% flowering (FLO₅₀) at plot level when 50% of the plants have developed stigmas, days to 50% physiological maturity (PSM₅₀) and percentage of productive tillers (PRO) at plot level. Data analysis was conducted using the Integrated Breeding Platform for Breeding Management System version 3.0.8 (IBP-BMS, 2014) and GenStat 15th Edition (Payne et al., 2012). The performance and ranking of genotypes was used to compare the consistency of the GEI methods. The models and computations for ANOVA, REML and AMMI indices for calculating ASVi were computed using GenStat 15 while the YSi, Wricke’s ecovalence, Finlay and Wilkinson, static stability, cultivar superiority and were computed using IBP-BMS 3.0.8.

Results

Assessing GEI effect using stability indices

The ANOVA showed that the main effects of environments were significant (p<0.05) on GY and PSM₅₀ and highly significant (p<0.001) for FLO₅₀, PAR and PRO. The main effects of the genotypes were also significantly (p<0.05) important for the yield-related traits except PAR. In addition, (GEI) was significant (p<0.05) for all the test traits.

Results for stability and GEI assessment for twenty most stable genotypes are shown in Tables 1-8. Generally, Cultivar superiority, REML, Yield stability index (YSi) and GGE biplot identified highly performing genotypes, as being stable with a significant positive correlation observed for most traits (Table 1) and among the methods (Table 2).
Table 1. Correlation between highly correlated stability methods and traits

| Traits  | Pi+REML | Pi+GGEbiplot | Pi+YSi | REML+YSi |
|---------|---------|--------------|--------|----------|
| GY      | 0.9**   | 0.5*         | 0.5*   | 0.5*     |
| FLO_{50} | -0.8**  | 0.5*         | -0.5*  | 0.5*     |
| PSM_{50} | -0.9**  | 0.5*         | -0.6*  | 0.6**    |
| PRO     | 0.9**   | -0.0ns       | 0.8**  | 0.7**    |
| PAR     | 0.6*    | -0.0ns       | 0.1ns  | -0.1ns   |

Traits: GY = Grain yield, FLO_{50} = Days to 50% flowering, PSM_{50} = Days to 50% physiological maturity, PRO = Percentage of productive tillers, PAR = Panicle area.

Methods: Pi = Cultivar superiority, REML = Restricted maximum likelihood, YSi = Yield stability index.

Table 2. Correlation among stability analysis methods for grain yield

| Methods    | Wi Static stability | Pi REML | ASVi GGE biplot | YSi |
|------------|---------------------|---------|-----------------|-----|
| bi         | -0.1                | -0.1    | -0.0            | 0.2 | -0.2 |
| Wi         | 1.0                 | 0.0     | 0.1             | 0.5*| -0.2 |
| Static stability | 1.0           | -0.5*   | -0.6*           | 0.3 | -0.6*|
| Pi         | 1.0                 | 0.9**   | 0.1             | 0.5*| 0.5* |
| REML       | 1.0                 | 0.0     | 0.5*            |     | 0.5* |
| ASVi       | 1.0                 | 0.0     | 0.0             | -0.3|     |
| GGE biplot | 1.0                 | 0.1     |                 |     | 0.1  |

Methods: bi = Finlay and Wilkinson, Wi = Wricke’s ecovalence, Pi = Cultivar superiority, REML = Restricted maximum likelihood, ASVi = Ammi stability value, YSi = Yield stability index.

High correlation was observed between Cultivar superiority and REML, Cultivar superiority and GGE biplot, Cultivar Superiority and YSi, REML and YSi and Finley and Wilkinson and Static stability for all the traits. However, significant negative correlation was observed between Finley and Wilkinson and Static stability for most traits except grain yield.

Some consistency in genotype ranking was observed between Finley and Wilkinson and Static stability then Wricke’s ecovalence, static stability and ASVi for all the traits while a similar pattern was observed between Cultivar superiority and REML for grain yield, panicle area and percentage of productive tillers. Similarity was also observed between Wricke’s ecovalence and GGE biplot for days to 50% physiological maturity and percentage of productive tillers.

Grain yield (GY)

Results of ranking of the twenty most stable genotypes for grain yield are shown in Table 3. Generally, differences in the ranking of the genotypes existed for all the seven stability analysis methods with Finley and Wilkinson, Wricke’s ecovalence, static stability and ASVi identifying low
Table 3. Genotype by environment analysis for grain yield (kg ha\(^{-1}\))

| Rank | Genotype | Finley and Wilkenson Means | Wricke’s ecovalence Means | Static stability | Cultivar superiority | REML Genotype Means | ASVi Genotype Means | GGE biplot Genotype Means | Yield stability index |
|------|-----------|---------------------------|---------------------------|-----------------|---------------------|---------------------|---------------------|-------------------------|-----------------------|
| 1    | 1x8       | 1820                      | 2                          | 1812            | 2x12                | 1482                | 6x10                | 2506                    | 3x11                  | 2143                  |
| 2    | 1x16      | 1585                      | 8                          | 2005            | 6x16                | 1306                | 3x11                | 2413                    | 3x11                  | 2257                  |
| 3    | 1x9       | 1977                      | 6                          | 2054            | 1x16                | 1585                | 4x16                | 2344                    | 6x8                   | 2210                  |
| 4    | 4x12      | 1712                      | 9                          | 2027            | 4x12                | 1712                | 6x8                  | 2387                    | 5x12                  | 2183                  |
| 5    | 6x16      | 1306                      | 12                         | 1878            | 1x11                | 1427                | 3x12                | 2257                    | 8                     | 2173                  |
| 6    | 2x12      | 1482                      | 3x9                         | 1797            | 1x12                | 1518                | 1x14                | 2355                    | 6x9                   | 2172                  |
| 7    | 2x15      | 2169                      | 4x7                         | 1903            | 16                   | 1799                | 5x15                | 2230                    | 4x16                  | 2171                  |
| 8    | 4x13      | 2026                      | 4                          | 1952            | 5x16                | 1621                | 5x12                | 2322                    | 3x12                  | 2154                  |
| 9    | 1x7       | 1671                      | 3x7                         | 1784            | 1                   | 1787                | 6x9                 | 2371                    | 5x13                  | 2102                  |
| 10   | 1x13      | 1906                      | 4x10                        | 1680            | 3x14                | 1642                | 6x7                 | 2149                    | 5x8                   | 2076                  |
| 11   | 2x7       | 1723                      | 13                          | 1907            | 4x7                 | 1903                | 2x15                | 2169                    | 1x15                  | 2071                  |
| 12   | 3x16      | 1923                      | 16                          | 1799            | 4x10                | 1680                | 4x11                | 2100                    | 6x12                  | 2057                  |
| 13   | 6x14      | 2003                      | 2x9                         | 1822            | 7                   | 1869                | 5x8                 | 2187                    | 5x15                  | 2046                  |
| 14   | 3x14      | 1642                      | 3                           | 1864            | 4                   | 1952                | 6                   | 2054                    | 4x11                  | 2041                  |
| 15   | 4x15      | 1821                      | 3x12                         | 2257            | 4x15                | 1821               | 9                   | 2027                    | 6x7                   | 2023                  |
| 16   | 5x15      | 2230                      | 1                           | 1787            | 2                   | 1812                | 6x14                | 2003                    | 2x15                  | 2111                  |
| 17   | 1x12      | 1518                      | 10                          | 1855            | 14                   | 1922                | 8                   | 2005                    | 5x9                   | 2002                  |
| 18   | 6x13      | 1914                      | 7                           | 1869            | 3x13                | 1572                | 4x14                | 2054                    | 6                     | 1992                  |
| 19   | 1x11      | 1427                      | 14                          | 1922            | 3x10                | 1463                | 15                   | 1965                    | 4x14                  | 1988                  |
| 20   | 5x16      | 1621                      | 15                          | 1965            | 3x9                 | 1797                | 5x13                | 2210                    | 4x8                   | 1976                  |
| Rank | Finley and Wilkenson ecovalence | Wricke’s superiority | Static stability | Cultivar superiority | REML | ASVi | GGE biplot | Yield stability |
|------|---------------------------------|----------------------|------------------|---------------------|------|------|-----------|----------------|
|      | Genotype                        | Means                | Genotype         | Means               | Genotype | Means | Genotype | Means | Genotype | Means | Genotype | Means | Genotype | Means | Genotype | Means |
| 1    | 5x13                            | 57.5                 | 12               | 56.4                | 4x14     | 55.9  | 5x7      | 62.8  | 2x11     | 53.1  | 2x14     | 54.6  | 6x8      | 59.9  | 2x14     | 54.6  |
| 2    | 4x14                            | 55.9                 | 10               | 57.7                | 13      | 57.3  | 4x15     | 61.4  | 1x9      | 53.6  | 2x16     | 56.5  | 4x13     | 60.3  | 11       | 55.8  |
| 3    | 1x13                            | 58.0                 | 11               | 55.8                | 5x10     | 58.3  | 3x16     | 60.4  | 1x11     | 54.6  | 12       | 56.4  | 4x16     | 59.9  | 2x10     | 55.6  |
| 4    | 2x12                            | 55.5                 | 1x7              | 56.3                | 4x12     | 59.4  | 4x8      | 60.9  | 3x12     | 54.6  | 1x7      | 56.3  | 4x10     | 60.6  | 1x7      | 56.3  |
| 5    | 4x10                            | 60.6                 | 6                | 57.5                | 6x14     | 55.6  | 6x8      | 59.9  | 2x12     | 54.9  | 4x11     | 57.5  | 4x8      | 60.9  | 1x10     | 54.8  |
| 6    | 3x10                            | 56.3                 | 4                | 58.6                | 2x7      | 58.6  | 4x10     | 60.6  | 2x14     | 54.9  | 10       | 57.7  | 1x6      | 60.0  | 12       | 56.4  |
| 7    | 5x9                             | 55.8                 | 4x11             | 57.5                | 10      | 57.7  | 4x13     | 60.3  | 6x13     | 55.0  | 13       | 57.3  | 1x14     | 58.4  | 2x16     | 56.5  |
| 8    | 4x12                            | 59.4                 | 2x16             | 56.5                | 5x9      | 55.8  | 2x15     | 59.1  | 1x10     | 55.1  | 8        | 57.5  | 6x10     | 58.4  | 6x14     | 55.6  |
| 9    | 3x11                            | 56.1                 | 7                | 58.2                | 12      | 56.4  | 1x16     | 60.0  | 2x9      | 55.6  | 11       | 55.8  | 5x16     | 57.9  | 5x12     | 55.9  |
| 10   | 5x10                            | 58.3                 | 6x16             | 57.6                | 3x7      | 56.5  | 6x15     | 59.8  | 3x8      | 55.7  | 4        | 58.6  | 11       | 55.3  | 6x12     | 56.6  |
| 11   | 3x13                            | 55.9                 | 1                | 57.8                | 3x14     | 58.9  | 3x14     | 58.9  | 2x10     | 55.8  | 6x12     | 56.6  | 1x15     | 58.0  | 13       | 57.3  |
| 12   | 5x7                             | 62.8                 | 8                | 57.5                | 1x10     | 54.8  | 1x12     | 58.6  | 6x14     | 55.8  | 6        | 57.5  | 2x15     | 57.5  | 4x11     | 57.5  |
| 13   | 1x12                            | 58.6                 | 16               | 58.5                | 11      | 55.8  | 4x16     | 59.9  | 5x8      | 56.0  | 1x16     | 60.0  | 1x12     | 58.6  | 2x9      | 54.8  |
| 14   | 13                              | 57.3                 | 2x10             | 55.6                | 9       | 57.2  | 4x12     | 59.4  | 6x11     | 56.0  | 2x10     | 55.6  | 5x13     | 57.5  | 3        | 56.3  |
| 15   | 5x11                            | 56.1                 | 1x10             | 54.8                | 1       | 57.8  | 3x9      | 57.9  | 11       | 56.0  | 16       | 58.5  | 6x9      | 57.6  | 3x12     | 54.1  |
| 16   | 4x13                            | 60.3                 | 13               | 57.3                | 5x11     | 56.1  | 2x7      | 58.6  | 4x14     | 56.0  | 6x16     | 57.6  | 16       | 58.7  | 5x8      | 55.4  |
| 17   | 4x15                            | 61.4                 | 5x12             | 55.9                | 6x9      | 57.6  | 6x10     | 58.4  | 5x12     | 56.1  | 2x7      | 58.6  | 3x14     | 58.9  | 6        | 57.5  |
| 18   | 6x13                            | 56.4                 | 6x14             | 55.6                | 3x13     | 55.9  | 4x7      | 60.9  | 3x7      | 56.2  | 7        | 58.2  | 14       | 56.6  | 8        | 57.5  |
| 19   | 3x7                             | 56.5                 | 6x11             | 56.5                | 5x7      | 57.6  | 16       | 58.5  | 1x13     | 56.2  | 1        | 57.8  | 1x8      | 57.4  | 4x14     | 55.9  |
| 20   | 6x14                            | 55.6                 | 1x15             | 58.0                | 3x11     | 56.1  | 15       | 58.3  | 1x7      | 56.2  | 6x14     | 55.6  | 2x11     | 51.6  | 4x9      | 56.1  |

1 = ICMV3771, 2 = Manganara, 3 = Okashana2, 4 = ITMV8001, 5 = SDMV94001, 6 = Shibe, 7 = Exbornu, 8 = CIVT9206, 9 = GGB8735, 10 = ICMV221, 11 = ICMV221 white, 12 = KatPM1, 13 = Okoa, 14 = SDMV96053, 15 = Sosank, 16 = Okollo
Table 5. Genotype by environment analysis for days to 50% physiological maturity

| Rank | Finley and Wilkenson | Wricke’s ecovalence | Static stability | Cultivar superiority | REML | ASVi | GGE biplot | Yield stability index |
|------|----------------------|---------------------|----------------|-----------------------|------|------|-----------|-----------------------|
|      | Genotype | Means | Genotype | Means | Genotype | Means | Genotype | Means | Genotype | Means | Genotype | Means | Genotype | Means | Genotype | Means | Genotype | Means |
| 1    | 1x13     | 84.3  | 12     | 86.2  | 4x14     | 86.3  | 4x16     | 95.3  | 2x11     | 82.0  | 13     | 87.7  | 4x10     | 91.3  | 2x9     | 81.6  |
| 2    | 5x13     | 88.6  | 4x11    | 87.1  | 3x7      | 87.4  | 4x7      | 94.5  | 2x9      | 82.2  | 12     | 86.2  | 4        | 90.9  | 1x10    | 83.5  |
| 3    | 5x10     | 89.5  | 6       | 87.5  | 6x15     | 89.6  | 4x15     | 92.8  | 3x12     | 82.8  | 6      | 87.5  | 3        | 87.2  | 6x14    | 83.4  |
| 4    | 3x14     | 89.8  | 11      | 85.2  | 1x10     | 83.5  | 3x16     | 91.5  | 1x9      | 83.0  | 4x11    | 87.1  | 2x12     | 84.4  | 11      | 85.2  |
| 5    | 4x14     | 86.3  | 5x11    | 83.5  | 5x10     | 89.5  | 5x7      | 93.0  | 1x13     | 83.0  | 11     | 85.2  | 4x12     | 91.0  | 12      | 86.2  |
| 6    | 6x16     | 87.4  | 15      | 88.2  | 6x14     | 83.4  | 4x12     | 91.0  | 6x14     | 83.2  | 3x8     | 86.6  | 5x12     | 84.9  | 5x11    | 83.5  |
| 7    | 6x9      | 88.0  | 16      | 90.1  | 6x16     | 87.4  | 4x8      | 91.9  | 1x11     | 83.3  | 8      | 88.0  | 12      | 86.8  | 2x11    | 81.5  |
| 8    | 3x7      | 87.4  | 1       | 87.7  | 6x9      | 88.0  | 4x10     | 91.3  | 5x11     | 83.4  | 1x10    | 83.5  | 11      | 84.3  | 3x8     | 86.6  |
| 9    | 6x15     | 89.6  | 10      | 87.9  | 10       | 87.9  | 6x8      | 91.5  | 1x10     | 83.5  | 1x16    | 90.4  | 3x12     | 83.0  | 2x10    | 85.0  |
| 10   | 1x10     | 83.5  | 4x12    | 91.0  | 13      | 87.7  | 4x13     | 91.5  | 2x12     | 83.5  | 2x7     | 88.4  | 3x14     | 89.8  | 4x11    | 87.1  |
| 11   | 5x7      | 93.0  | 2x16    | 88.3  | 3x11     | 84.3  | 16       | 90.1  | 3x11     | 84.0  | 6x14    | 83.4  | 16      | 90.3  | 4x14    | 86.3  |
| 12   | 2x12     | 84.4  | 6x12    | 86.5  | 9       | 88.0  | 1x16     | 90.4  | 5x8      | 84.3  | 2x9     | 81.6  | 4x11     | 87.1  | 6      | 87.5  |
| 13   | 5x9      | 89.5  | 4       | 90.0  | 1x13     | 84.3  | 4        | 90.0  | 2x10     | 84.4  | 1x15    | 87.6  | 6      | 87.6  | 2x14    | 84.1  |
| 14   | 6x14     | 83.4  | 6x10    | 88.4  | 2x12     | 84.4  | 6x15     | 89.6  | 2x14     | 84.7  | 1x14    | 89.6  | 4x9     | 87.3  | 13      | 87.7  |
| 15   | 1x14     | 89.6  | 13      | 87.69 | 5x11     | 83.5  | 1x12     | 90.3  | 11       | 84.9  | 10      | 87.9  | 3x15     | 88.4  | 6x12    | 86.5  |
| 16   | 4x15     | 92.8  | 7       | 89.0  | 1        | 87.7  | 7        | 89.0  | 5x12     | 84.9  | 5x11    | 83.5  | 9      | 86.4  | 3x11    | 84.3  |
| 17   | 4x16     | 95.3  | 5x12    | 84.9  | 3x13     | 85.1  | 5x10     | 89.5  | 3x13     | 85.0  | 15      | 88.2  | 15      | 89.0  | 5x12    | 84.9  |
| 18   | 3x11     | 84.3  | 6x14    | 83.6  | 4       | 87.5  | 1x8      | 90.3  | 4x14     | 85.8  | 4x14    | 86.3  | 5x11     | 83.5  | 2x8     | 87.0  |
| 19   | 13       | 87.7  | 3       | 86.5  | 3x14     | 89.8  | 3x14     | 89.8  | 6x7      | 85.9  | 2x10    | 85.0  | 5x8      | 83.6  | 8      | 88.0  |
| 20   | 1x12     | 90.3  | 2       | 86.0  | 17       | 85.7  | 5x9      | 89.5  | 2x8      | 85.9  | 2x8     | 87.0  | 2x11     | 81.5  | 5x15    | 87.0  |

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| Rank | Finley and Wilkenson Genotype Means | Wricke’s ecovalence Genotype Means | Static stability Genotype Means | Cultivar superiority Genotype Means | REML Genotype Means | ASVi Genotype Means | GGE biplot Genotype Means | Yield stability index Genotype Means |
|------|------------------------------------|------------------------------------|---------------------------------|-------------------------------------|--------------------|---------------------|------------------------|-----------------------------|
| 1    | 2x15                               | 71.04                              | 1                               | 82.35                               | 1                 | 92.49               | 92.49                  | 19.16                       | 3                         | 82.22                           | 1x9                         | 92.49                       |
| 2    | 1x14                               | 68.5                               | 14                              | 82.68                               | 5                 | 81.24               | 91.92                  | 6                  | 91.28                       | 1                          | 82.35                           | 4x13                        | 86.76                       | 1x13                         | 89.46                       |
| 3    | 6x10                               | 86.24                              | 5                               | 83.53                               | 5x12               | 91.92               | 91.23                  | 1                 | 91.16                       | 3x12                       | 86.35                           | 2                          | 82.15                           | 4x7                         | 89.94                       |
| 4    | 6x11                               | 85.5                               | 2                               | 81.69                               | 2x11               | 91.23               | 92.17                  | 6                 | 91.78                       | 5x12                        | 86.85                           | 3                          | 82.68                           | 6                           | 84.21                       | 4x10                         | 90.56                       |
| 5    | 5x9                                | 78.96                              | 13                              | 87.24                               | 5x10               | 81.55               | 92.14                  | 4                 | 90.84                       | 2x11                        | 87.72                           | 5                           | 83.53                           | 5                           | 83.53                       | 1                           | 85.93                       | 4x14                         | 89.79                       |
| 6    | 6x12                               | 84.27                              | 6                               | 82.65                               | 9                  | 82.26               | 89.91                  | 4                 | 90.8                        | 4x10                        | 87.72                           | 7                           | 85.19                           | 1                           | 85.19                       | 5                           | 84.82                       | 7                           | 85.19                       |
| 7    | 5x10                               | 81.55                              | 11                              | 85.61                               | 6                  | 82.65               | 89.94                  | 1                 | 89.72                       | 1x13                        | 87.72                           | 7                           | 85.93                           | 3                           | 86.58                       | 1x10                         | 89.33                       |
| 8    | 1x9                                | 92.49                              | 10                              | 82.99                               | 6x15               | 73.77               | 89.79                  | 4                 | 89.36                       | 4x11                        | 87.72                           | 2                           | 81.69                           | 5                           | 84.82                       | 7                           | 85.19                       |
| 9    | 3x13                               | 86.57                              | 4                               | 85.5                                | 2x16               | 82.53               | 87.24                  | 5                 | 89.3                        | 5x7                         | 87.24                           | 10                          | 82.99                           | 3                           | 86.58                       | 1x10                         | 89.33                       |
| 10   | 5x12                               | 91.92                              | 9                               | 82.26                               | 5                  | 83.53               | 87.72                  | 4                 | 89.24                       | 4x14                        | 88.46                           | 13                          | 87.24                           | 2x15                        | 81.48                           | 4x11                         | 89.19                       |
| 11   | 1x16                               | 86.13                              | 4                               | 78.88                               | 1                  | 83.25               | 89.46                  | 4                 | 88.46                       | 4x14                        | 88.46                           | 13                          | 87.24                           | 2x15                        | 81.48                           | 4x11                         | 89.19                       |
| 12   | 5x8                                | 91.24                              | 12                              | 82.5                                | 2x13               | 87.98               | 89.41                  | 6                 | 82.65                       | 4x9                         | 88.41                           | 12                          | 82.1                           | 2x16                         | 83.39                           | 4x13                         | 86.75                       |
| 13   | 4x14                               | 89.79                              | 2x16                             | 82.53                               | 3x12               | 86.35               | 87.54                  | 4                 | 89.94                       | 4x7                         | 89.94                           | 12                          | 82.1                           | 1                           | 82.1                        | 10                           | 82.99                       |
| 14   | 4x15                               | 74.8                               | 7                               | 85.19                               | 5x9                | 78.96               | 88.52                  | 3                 | 87.53                       | 3x11                        | 87.53                           | 11                          | 84.23                           | 6x12                        | 84.27                           | 2x11                         | 92.13                       |
| 15   | 3x12                               | 86.35                              | 4x9                             | 88.91                               | 4x9                | 88.91               | 85.61                  | 6                 | 87.38                       | 6x8                         | 87.38                           | 4                           | 85.5                            | 9                           | 85.03                           | 4                           | 85.5                       |
| 16   | 6x14                               | 87.72                              | 12                              | 82.5                                | 10                 | 82.99               | 89.19                  | 5                 | 87.18                       | 5x14                        | 87.18                           | 9                           | 82.26                           | 2x8                         | 81.38                           | 2x13                        | 87.98                       |
| 17   | 2x13                               | 87.98                              | 1x13                             | 89.46                               | 14                 | 82.68               | 86.13                  | 13                | 87.15                       | 2x11                        | 91.23                           | 5x15                        | 84.62                           | 9                           | 82.26                           |                                |                            |
| 18   | 2x12                               | 75.51                              | 2x9                             | 81.66                               | 6x14               | 87.72               | 86.75                  | 6                 | 87.08                       | 4x13                        | 87.08                           | 4x16                        | 78.88                           | 6x16                        | 77.71                           | 1x11                        | 84.23                       |
| 19   | 6x15                               | 73.77                              | 3                               | 82.97                               | 6x7                | 92.17               | 86.97                  | 2                 | 86.85                       | 4x13                        | 86.85                           | 4x9                         | 88.91                           | 3x10                        | 81.81                           | 1                           | 82.35                       |
| 20   | 5x11                               | 75.14                              | 6x7                             | 92.17                               | 6x11               | 88.52               | 92.17                  | 2                 | 86.85                       | 4x13                        | 87.08                           | 4x9                         | 88.91                           | 3x10                        | 81.81                           | 1                           | 82.35                       |

1= ICMV3771, 2 = Manganara, 3 = Okashana2, 4 = ITMV8001, 5 = SDMV94001, 6 = Shibe, 7 = Exbornu, 8 = CIVT9206, 9 = GGB8735, 10 = ICMV221, 11 = ICMV221 white, 12 = KatPM1, 13 = Okoa, 14 = SDMV96053, 15 = Sosank, 16 = Okollo
| Rank | Genotype | Finley and Wilkenson Means | Genotype | Wricke’s ecovalence Means | Genotype | Static stability Means | Genotype | Cultivar superiority Means | Genotype | REML Means | Genotype | ASVi Means | Genotype | GGE biplot Means | Genotype | Yield stability index |
|------|----------|-----------------------------|----------|---------------------------|----------|------------------------|----------|---------------------------|----------|-----------|----------|------------|----------|-----------------------|----------|----------------------|
| 1    | 2x15     | 71.0                        | 1        | 82.4                      | 1x9      | 92.5                   | 1x9      | 92.5                      | 1x9      | 92.2       | 11       | 85.6       | 3        | 82.2                  | 1x9      | 92.5                  |
| 2    | 1x14     | 68.5                        | 14       | 82.7                      | 5x8      | 91.2                   | 5x12     | 91.9                      | 6x7      | 91.3       | 1        | 82.4       | 4x13     | 86.8                  | 1x13     | 89.5                  |
| 3    | 6x10     | 86.2                        | 5        | 83.5                      | 5x12     | 91.9                   | 2x11     | 91.2                      | 5x8      | 91.2       | 3x12     | 86.4       | 2        | 82.2                  | 4x7      | 89.9                  |
| 4    | 6x11     | 88.5                        | 2        | 81.7                      | 2x11     | 91.2                   | 6x7      | 92.2                      | 5x12     | 91.0       | 14       | 82.7       | 6        | 84.2                  | 4x10     | 90.6                  |
| 5    | 5x9      | 79.0                        | 13       | 87.2                      | 5x10     | 81.6                   | 6x11     | 87.7                      | 4x7      | 89.2       | 13       | 87.2       | 2x15     | 81.5                  | 4x11     | 89.2                  |
| 6    | 6x12     | 84.3                        | 6        | 82.7                      | 9x12     | 89.9                   | 6x14     | 87.7                      | 4x7      | 89.2       | 5        | 83.5       | 1x10     | 85.9                  | 4x14     | 89.8                  |
| 7    | 5x10     | 81.6                        | 11       | 85.6                      | 6x11     | 87.7                   | 4x7      | 89.2                      | 13       | 87.2       | 7        | 85.2       | 10       | 84.6                  | 11       | 85.6                  |
| 8    | 1x9      | 92.5                        | 10       | 83.0                      | 6x15     | 73.8                   | 4x14     | 89.8                      | 4x7      | 89.2       | 2        | 81.7       | 5x13     | 84.8                  | 7        | 85.2                  |
| 9    | 3x13     | 86.8                        | 4        | 85.5                      | 2x16     | 82.5                   | 13       | 87.2                      | 5x7      | 89.3       | 10       | 83.0       | 3x13     | 86.6                  | 1x10     | 85.9                  |
| 10   | 5x10     | 91.9                        | 9        | 82.3                      | 5x11     | 83.5                   | 6x14     | 87.7                      | 4x7      | 89.2       | 13       | 87.2       | 2x15     | 81.5                  | 4x11     | 89.2                  |
| 11   | 1x16     | 86.1                        | 4x16     | 78.9                      | 1        | 82.4                   | 1x13     | 89.5                      | 4x14     | 88.5       | 5x8      | 91.2       | 5x16     | 76.6                  | 1x16     | 86.1                  |
| 12   | 5x8      | 91.2                        | 2x11     | 91.2                      | 12       | 82.5                   | 2x13     | 88.0                      | 4x9      | 88.4       | 6        | 82.7       | 2x16     | 83.4                  | 4x13     | 86.8                  |
| 13   | 4x14     | 89.8                        | 2x16     | 82.5                      | 3x12     | 86.4                   | 3x12     | 86.4                      | 2x14     | 87.5       | 4x7      | 89.9       | 12       | 82.1                  | 10       | 83.0                  |
| 14   | 4x15     | 74.8                        | 7        | 85.2                      | 5x9      | 79.0                   | 6x11     | 88.5                      | 3x11     | 87.5       | 11       | 84.2       | 6x12     | 84.3                  | 2x11     | 91.2                  |
| 15   | 3x12     | 86.4                        | 4x9      | 88.9                      | 4x9      | 88.9                   | 11       | 85.6                      | 6x8      | 87.4       | 4        | 85.5       | 9        | 85.0                  | 4        | 85.5                  |
| 16   | 6x14     | 87.7                        | 12       | 82.5                      | 10       | 83.0                   | 4x11     | 89.2                      | 5x14     | 87.2       | 9        | 82.3       | 2x8      | 81.4                  | 2x13     | 88.0                  |
| 17   | 2x13     | 88.0                        | 13x15    | 89.5                      | 14       | 82.7                      | 1x16     | 86.1                      | 13       | 87.2       | 2x11     | 91.2       | 5x15     | 84.6                  | 9        | 82.3                  |
| 18   | 2x12     | 75.5                        | 2x9      | 81.7                      | 6x14     | 87.7                   | 4x13     | 86.8                      | 6x11     | 87.1       | 4x16     | 78.9       | 6x16     | 77.7                  | 1x11     | 84.3                  |
| 19   | 6x15     | 73.8                        | 3        | 83.0                      | 6x7      | 92.2                   | 4        | 85.5                      | 4x13     | 87.1       | 4x9      | 88.9       | 3x10     | 81.8                  | 1        | 82.4                  |
| 20   | 5x11     | 75.1                        | 6x7      | 92.2                      | 8x15     | 86.5                   | 8x14     | 89.7                      | 6x16     | 86.9       | 2x16     | 82.5       | 2x9      | 81.7                  | 2x14     | 87.6                  |

1 = ICMV3771, 2 = Manganara, 3 = Okashana2, 4 = ITMV8001, 5 = SDMV94001, 6 = Shibe, 7 = Exbornu, 8 = CIVT9206, 9 = GGB8735, 10 = ICMV221, 11 = ICMV221white, 12 = KatPM1, 13 = Okoa, 14 = SDMV96053, 15 = Sosank, 16 = Okollo
Table 8. Genotype by environment analysis for panicle area

| Rank | Finley and Wilkenson ecovalence | Wricke’s superiority | Static stability | Cultivar superiority | REML | ASVi | GGE biplot | Yield stability index |
|------|---------------------------------|----------------------|------------------|----------------------|-------|------|------------|-----------------------|
|      | Genotype                        | Means                | Genotype         | Means                | Genotype | Means | Genotype   | Means                | Genotype | Means | Genotype | Means | Genotype | Means | Genotype | Means | Genotype | Means |
| 1    | 4x12                            | 759.8                | 6                 | 572.3                | 4x7      | 406.2 | 3x15       | 1065.3               | 2x15     | 1103.5 | 4x9       | 516.1 | 4        | 536.5 | 1x16     | 663.7 |
| 2    | 3x15                            | 1065.3               | 12                 | 608.2                | 4x11     | 379.8 | 2x8        | 754.3                | 4x15     | 1093.9 | 6         | 572.3 | 5x12     | 770.2 | 1x13     | 654.7 |
| 3    | 4x7                             | 406.2                | 5x14               | 430.0                | 4x16     | 408.0 | 3x10       | 794.4                | 6x15     | 956.0  | 5x14      | 430.0 | 2x7      | 642.2 | 4x12     | 759.8 |
| 4    | 2x8                             | 754.3                | 4x9                | 516.1                | 4        | 533.2 | 6x8        | 718.5                | 6x10     | 942.7  | 12        | 608.2 | 4x9      | 516.1 | 10       | 600.0 |
| 5    | 6x8                             | 718.5                | 3x9                | 434.9                | 2x9      | 654.7 | 4x12       | 759.8                | 5x12     | 835.1  | 5x11      | 485.8 | 9        | 499.8 | 9        | 597.3 |
| 6    | 2x9                             | 654.7                | 1x10               | 437.1                | 6x14     | 547.2 | 15         | 655.5                | 6x16     | 759.4  | 5x10      | 418.1 | 14       | 515.9 | 4x15     | 749.5 |
| 7    | 4x16                            | 408.0                | 3x12               | 390.4                | 2x11     | 513.1 | 6x15       | 809.2                | 9        | 757.9  | 3x9       | 434.9 | 6x16     | 598.3 | 1x11     | 635.2 |
| 8    | 4x11                            | 379.8                | 5x10               | 418.1                | 5x11     | 485.8 | 3          | 603.3                | 6x12     | 744.5  | 6x11      | 362.6 | 4x11     | 379.8 | 8        | 563.9 |
| 9    | 6x14                            | 547.2                | 2                  | 598.4                | 6x11     | 362.6 | 8          | 563.9                | 2x9      | 729.5  | 1x10      | 437.1 | 4x16     | 408.0 | 2x8      | 754.3 |
| 10   | 2x11                            | 513.1                | 6x11               | 362.6                | 2x12     | 472.6 | 6x10       | 812.9                | 6x8      | 716.3  | 10        | 600.0 | 6x12     | 634.5 | 4x13     | 643.2 |
| 11   | 4                               | 533.2                | 6x9                | 436.1                | 11       | 477.5 | 12         | 608.2                | 1x11     | 710.5  | 3x12      | 390.4 | 4x14     | 468.7 | 7        | 551.6 |
| 12   | 2x15                            | 728.3                | 6x13               | 508.6                | 6x7      | 562.7 | 10         | 600.0                | 5x11     | 674.1  | 2         | 598.4 | 15       | 734.6 | 1x12     | 579.1 |
| 13   | 6x7                             | 562.7                | 1x15               | 446.2                | 6x12     | 634.5 | 1x16       | 663.7                | 3x15     | 673.8  | 6x9       | 436.1 | 1x7      | 547.3 | 2x10     | 656.1 |
| 14   | 4x15                            | 749.5                | 10                 | 600.0                | 6x8      | 718.5 | 4x8        | 526                  | 16       | 633.0  | 6x13      | 508.6 | 2x15     | 749.3 | 2x15     | 728.3 |
| 15   | 5x11                            | 485.8                | 11                 | 477.5                | 6x16     | 598.3 | 4x15       | 749.5                | 12       | 610.2  | 11        | 477.5 | 3x11     | 591.0 | 3x10     | 794.4 |
| 16   | 2x12                            | 472.6                | 3x7                | 491.2                | 12       | 680.2 | 2x7        | 642.2                | 2x7      | 602.3  | 1x15      | 446.2 | 1x11     | 635.2 | 2x9      | 654.7 |
| 17   | 6x16                            | 598.3                | 14                 | 538.8                | 9        | 597.3 | 2          | 598.4                | 15       | 601.7  | 6x16      | 598.3 | 2x6      | 599.5 | 1x7      | 547.3 |
| 18   | 6x11                            | 362.6                | 3x16               | 452.6                | 2        | 598.4 | 6x12       | 634.5                | 1x13     | 593.0  | 16        | 562.5 | 6x15     | 809.2 | 2x7      | 642.2 |
| 19   | 5x7                             | 623.9                | 3x8                | 470.4                | 6x13     | 508.6 | 3x12       | 770.2                | 2x7      | 591.4  | 3x8        | 470.4 | 13       | 576.1 | 1        | 537.7 |
| 20   | 9                               | 597.3                | 5                  | 526.9                | 6        | 572.3 | 2x15       | 728.3                | 2        | 590.1  | 3x7        | 491.2 | 2x13     | 483.9 | 3x15     | 1065.3 |

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Genotype by environment analysis methods for yield-related traits of pearl millet yielding (<2000 kg ha\(^{-1}\)) genotypes as being the most stable across environments; while Cultivar superiority, REML, GGE biplot and YSi identified high yielding genotypes as being the most stable. A significant positive correlation was also observed between Cultivar superiority, REML, GGE biplot and YSi although the correlation was stronger between Cultivar superiority and REML where both methods identified 16 genotypes as being stable but with a slight difference in ranking. The Wricke’s ecovalence, static stability and ASVi identified 11 out 20 genotypes as being stable although ranked differently.

**Days to 50% flowering (FLO\(_{50}\))**
The ranking of the genotypes by the methods was different for the trait, with similarity existing only in number of genotypes identified by each method (Table 4). The Finley and Wilkinson and Static stability had 10 genotypes in common, 6 with Cultivar superiority and REML, while Wricke’s ecovalence and ASVi had 16 in common, 8 with static stability and 7 with REML. Cultivar superiority also had 9 genotypes in common with GGEbiplot and no genotype in common with REML.

**Days to 50% physiological maturity (PSM\(_{50}\))**
Variation in genotypes and ranking was also observed across the methods for days to 50% physiological maturity. In addition, the similarity level in number of genotypes commonly identified also varied (Table 5). The Finley and Wilkinson and Static stability methods had the highest number (13) of genotypes in common but ranked differently. This was followed by Wricke’s ecovalence and GGE biplot (11), then Wricke’s ecovalence and ASVi (9). The cultivar superiority had no genotype in common with REML while it had only one with ASVi.

**Percentage of productive tillers (PRO)**
Differences in genotypes and ranking by the stability methods were observed for productive tillers (Table 7). The Cultivar superiority and REML identified 15 of the 20 genotypes in common and 9 out of 20 with Finley and Wilkinson’s while Wricke’s ecovalence and ASVi had 14 of 20 most stable genotypes in common but differences existed in ranking. Using static stability, 6 out of 20 genotypes were common with REML while for GGE biplot, 6 genotypes ranked in common with Wricke’s ecovalence method. The ranking for all the genotypes was different in all the stability methods tested irrespective of the commonality observed.

**Panicle area (PAR)**
Variation in ranking of the most stable genotypes by the tested stability methods was also observed for panicle area although some similarities among the methods existed (Table 8). The Finley and Wilkinson and static stability had 14 genotypes in common of the 20 most stable; while Cultivar stability and REML methods identified 12 genotypes in common. In addition, Wricke’s ecovalence and ASVi identified 17 common genotypes out of 20 most stable genotypes across environments. The GGE biplot identified 6 common genotypes as Cultivar superiority and REML while 5 common genotypes were identified by Finley and Wilkinson and Static stability.

**Discussion**
Across the evaluation sites, yield ranged between 1427 kg ha\(^{-1}\) to 2506 kg ha\(^{-1}\). The ANOVA indicated significant variation
among the genotypes tested and the GEI, showing that the multiplicative interaction of the genotypes and environments affected the performance of the test materials as also reported by Subi et al. (2013). However, as noted by Crossa (1990), ANOVA does not explore the underlying structure within the GEI and thus other methods were adapted. Significant correlation among the Cultivar superiority with REML, YSi and GGE biplot shows that a prediction of comparable results can be revealed when any of the methods is used independently with minimal variation in the ranking of the genotypes.

Significant correlation was also observed elsewhere between Cultivar superiority and YSi in cotton (Blanche Sr., 2005) and Faba bean (Temesgena et al., 2015) studies. These correlated methods aid in simultaneously selecting stable and high yielding genotypes unlike the Finlay and Wilkinson, Wricke’s ecovalence, ASVi and Static stability which, in this study, identified mostly low yielding genotypes as being the most stable. Except ASVi, similar observations were made by Mohammadi and Amri (2008) in studies on wheat. Wrike’s method has also been reported to identify low yielding genotypes in sugar cane (Mendes de Paula et al., 2014) and field pea (Fikere et al., 2014) as also observed in this study.

The various analysis methods ranked genotypes differently for the same traits across the test environments. Similar observations were also made by Pabale and Pandya (2010) when they compared Eberhart and Russell (1966), Perkins and Jinks (1968) and Freeman and Perkins (1971) models in ranking of pearl millet genotypes basing on grain yield. Mustapha and Bakari (2014) reported no similarity between static and cultivar superiority; while cultivar superiority and GGE biplot identified the same genotypes as being stable, but ranked them differently in pearl millet. In this study, Cultivar superiority and GGE biplot were significantly correlated for grain yield, days to 50% flowering and days to 50% physiological maturity; with a difference in ranking of genotypes. Variation in ranking of genotypes was also reported by Parmar et al. (2012) when they compared nonparametric tests in rice; Mosleh et al. (2012) when they compared Wricke’s ecovalence, Shukla stability variance, rank test, and Eberhart and Russell; and Namorato et al. (2009) when they compared AMMI and Eberhart and Russell methods in maize. The inconsistency in ranking was also reported by Alberts (2004) and Khosa (2012) when cultivar superiority, Finlay and Wilkinson, Wricke’s ecovalence and ASVi were compared in maize. In addition, Dehghani et al. (2008) also observed variation in ranking Lentil genotypes, although they observed similarity between Shukla and Wricke’s, cultivar superiority and Wricke’s ecovalence, Finlay and Wilkinson and cultivar superiority. However, in the present study the methods had no significant correlation. The lack of significant association and differential ranking of genotypes by ASVi and GGE biplot was also observed in wheat studies by Naroui Rad et al. (2013). Results showed no significant association between cultivar superiority and Finlay and Wilkinson’s methods as also reported by Purchase et al. (2000). On the contrary, Purchase et al. (2000) reported a significant correlation between ASVi and Wricke’s ecovalence as also noted by Alberts (2004). This implies that results from the comparisons may greatly depend on the method, types of genotypes and
environments being evaluated as also observed by Westcott (1986) and thus more than one method should be used to characterise and explore performance of genotypes across environments as also suggested by Lin and Binns (1988).

Acknowledgement

The National Semi Arid Resources Research Institute for financial support and the technical staff who helped with trial management and data collection.

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