Yield Stability in Forage Maize across Selected Test-Environments

By S. H. Mohammed & M. I. Mohammed

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Abstract- Assessing new maize cultivars requires studying both yield and stability performance across the major range of environments. Four trials were conducted in Sudan (Africa) during 2013 – 2014. Nine maize genotypes were investigated for forage yield stability across 8 test-environments created by a combination of 2 levels of location, season and watering regime assumed to impose respective effects of salt, heat and water stress. Wricke’s ecovalence, Eberhart-Russell and AMMI stability models were employed to study yield stability. The genotypes and watering regimes were arranged in RCB design in split-plot experiment. The study revealed maize hybrids having broad and specific responses to the studied environments with most genotypes showing consistent stability performance in the three models. Two of the 3 top-yielding hybrids showed relative stability whereas the third one exhibited specific adaptability to low yielding environments. It was concluded that yield stability could be better investigated if the varieties are purposely subjected to major factors affecting yield in a given domain. Different stability models were recommended to avoid limitations arising from using a single model. Keywords: wricke’s ecovalence, eberhart and russell, AMMI, GxE.

I. Introduction

Maize (Zea mays L.) is one of the World’s three most important cereal crops. It is the primary source for coarse-grain representing 55% of the World consumption of animal feed [1]. Although the crop is cultivated in a wide range of environments due to its relatively wide adaptability [2] it is the least tolerant to abiotic stresses among cereals. Drought, salinity and elevated temperatures coupled with low humidity [1] are among the major abiotic stresses that negatively impact maize production.

Identification of high yielding cultivars with wide adaptability is the ultimate aim of plant breeders. However, attaining this goal is complicated by the genotype x environment (GxE) interaction. Therefore, assessing of new cultivars must be based not only on their yielding ability but also on their stability and adaptability across broad range of environments to avoid the misleading results caused by GxE interaction and to identify cultivars having the adaptability to specific environments. Several models could be used to study GxE interaction. The Wricke’s ecovalence model [3] simply quantify the contribution of each genotype in GxE interaction as a measure of stability related directly to the non-additive structure. Joint linear regression is another widely used model in plant breeding for analyzing and interpreting GxE interaction and determining yield stability of genotypes. It involves the regression of genotype means on an environmental index [4] and provides means of testing whether the genotypes have characteristic linear responses to environmental change [5]. Additive main effects and multiplicative interaction (AMMI) model is a powerful tool in diagnosing GxE patterns of interaction [6]. It is a multimodal approach that proved useful in understanding complex genotype x environment interactions.

The objectives of this study were to investigate forage yield stability of maize hybrids subjected to predetermined test-environments reflecting various levels of abiotic stress.

II. Materials and Methods

The experiment was conducted in Khartoum State during 2013-2014 under two seasons (summer and winter) and two locations: Shambat (Lat. 15° 39’ N; Long. 32° 31’ E; Alt 380 masl) and Soba (Lat.15° 24’ N; Long.32° 32’ E; Alt 380 masl). In each location the trial was carried out in the Experimental Farm of the Agricultural Research Corporation (ARC).

a) Soil and climatic conditions

The soil at Shambat is well-drained loamy clay, non-saline and non-sodic, with pH ranging from 7.71 to 7.91. The soil at Soba is hazard by salinity (ECe = 12 - 14 dS/m) and sodality (ESP = 24 - 27, SAR = 16 –23) with high clay content, low infiltration and permeability, low organic matter, low nitrogen and high pH. The average min-max temperature during the winter season (Nov. –Feb.) ranged 15-20°C and 32-38°C whereas that at summer (April-July) ranged 25.0-28.4°C and 36.9-42.0 °C. The weather is dry in both growing seasons especially during winter. For further details of soil and climatic conditions see Appendices I through V.

b) The plant materials

The plant materials used in the study (Table 1) included nine maize genotypes comprising 8 hybrids plus one open-polinated cultivar. Six of the maize genotypes have already been released for commercial production in Sudan.

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Table 1: Plant material used in the study

| Genotypes   | Type/Color          | Source                  |
|-------------|---------------------|-------------------------|
| PAN6966     | Yellow maize hybrid | Pannar Co. South Africa |
| PAN-12      | Yellow maize hybrid | Pannar Co. South Africa |
| PAN-14      | Yellow maize hybrid | Pannar Co. South Africa |
| PAN6P-110   | Yellow maize hybrid | Pannar Co. South Africa |
| Hytech1100  | White maize hybrid  | MisrHytech Co. Egypt    |
| Hytech2066  | Yellow Maize hybrid | MisrHytech Co. Egypt    |
| Hytech2031  | White Maize hybrid  | MisrHytech Co. Egypt    |
| Hytech2055  | Yellow Maize hybrid | MisrHytech Co. Egypt    |
| Hudieba2    | Yellow Maize (open pollinated) | Agric. Res. Corporation (ARC) Sudan |

Table 2: The test-environments

| S. No. | Location | Season | Year    |
|--------|----------|--------|---------|
| 1      | Soba     | Winter | 13/2014 |
| 2      | Shambat  | Winter | 13/2014 |
| 3      | Soba     | Summer | 2014    |
| 4      | Shambat  | Summer | 2014    |
| 5      | Soba     | Summer | 2017    |
| 6      | Shambat  | Summer | 2017    |
| 7      | Soba     | Winter | 2017/18 |
| 8      | Shambat  | Winter | 2017/18 |

III. Data Collection and Statistical Analysis

Forage yield was estimated at the milk stage from the two inner rows of each plot leaving 0.5 m from each side of the ridge. The plants were cut at the ground level and weighed immediately using spring balance. Dry matter yield (DMY, t/ha) was estimated from a random sample of 0.5 kg taken from the fresh harvested plants in each plot and air-dried to a constant weight. Days to 50% tasselling, plant height, stem diameter and quality traits (NDF, ADF, CP) were studied but will not be highlighted in this study.

Analysis of variance was performed following the standard procedure of analyzing split plot in RCB design [7]. Combined analysis of variance to assess the magnitude of genotype-environment interaction (GEI) was performed. Then mean squares of GEI was used to test the effect of genotypes. Analysis of yield stability for nine maize genotypes was carried out over the eight environments using the following stability models:

a) Wricke’s ecovalence (Wi)

According to this model, the stability of the genotype is its interaction with environments, squared and summed across environments [3]. The formula of this model is as follows:

\[ Wi = \sum (Y_{ij} - \bar{Y}_j - \bar{Y}_i + \bar{Y}) \]  \[ 2 \]

Where:

- \( Y_{ij} \) = Mean of genotype i in environment j,
- \( \bar{Y}_j \) = Mean yield of genotype across environments,
- \( \bar{Y}_i \) = environment mean, \( \bar{Y} \) = Overall mean.

b) Eberhart and Russell Stability Regression Model

The equation underlying this model [5] is as follows:

\[ Y_{ij} = m + B_i I_j + \delta_i \]

Where:

- \( i = 1, 2, \ldots, g \) (number of genotypes)
- \( j = 1, 2, \ldots, s \) (number of environment)
- \( Y_{ij} \) = The mean yield of \( i^{th} \) genotype in the \( j^{th} \) environment.
- \( m \) = The mean of all genotypes overall environments
- \( B_i \) = The regression coefficient of the \( i^{th} \) genotype on environment index, which measures the response of this genotype to varying environments.
\[ Y_{ij} = \mu + G_i + E_j + \sum_{k=1}^{n} \lambda_k \alpha_{ik} r_{jk} + e_{ij} \]

Where:
- \( Y_{ij} \) is the yield of the \( i \)th genotype in the \( j \)th environment;
- \( \mu \) is the grand mean;
- \( G_i \) and \( E_j \) are the genotype and environment deviations from the grand mean, respectively;
- \( \lambda_k \) is the eigen value of the PCA analysis axis;
- \( \alpha_{ik} \) and \( r_{jk} \) are the genotype and environment principal component scores for axis \( k \);
- \( n \) is the number of principal components retained in the model;
- \( e_{ij} \) is the residual.

The statistical package Agrobase [9] was used to run the three models of stability analysis.

**IV. Results**

Mean squares from combined analysis of variance for forage yield of 9 maize genotypes over the 8 test-environments are presented in Table 3.

Differences among environments, genotypes and genotype by environment interaction were highly significant for forage yield.

Table 3: Mean squares from combined ANOVA for forage yield of nine maize genotypes studied over eight environments

| Source of variation | DF | Dry matter yield (t/ha) |
|---------------------|----|-------------------------|
| Environments (E)    | 7  | 178.137**               |
| Reps within (E)     | 16 | 0.714                   |
| Genotypes (G)       | 8  | 31.031**                |
| G×E                 | 56 | 3.293**                 |
| Residual            | 128| 0.472                   |

** = Highly significant at 0.01 probability level

**a) Wricke Ecovariance**

Wi-ecovariance stability values and mean performance of nine maize genotypes across eight environments for DMY are presented in Table 4. The genotype Hytech2055 ranked top in forage yield (10.8 t/ha) coupled with the second-lowest stability value (\( w_i = 2.961 \)). PAN12 ranked third in both yield (10.3 t/ha) and stability value (\( w_i = 3.475 \)). PAN14 exhibited the highest stability value (\( w_i = 2.517 \)), coupled with the lowest forage yield (7.75 t/ha). In contrast, Hytech2031 averaged the second-top yield (10.5 t/ha) coupled with the second-highest stability value (\( w_i = 9.850 \)).

Table 4: Stability values (Wi-ecovariance) and mean performance in dry matter yield (DMY) of maize genotype

| Genotypes     | DMY (t/ha) | Wi-ecovariance† | Variations explained (%) |
|---------------|------------|-----------------|--------------------------|
| PAN6966       | 8.38 (6)   | 5.253 (5)       | 8.55                     |
| PAN12         | 10.3 (3)   | 3.475 (3)       | 5.65                     |
| PAN14         | 7.75 (9)   | 2.517 (1)       | 4.09                     |
| PAN6P-110     | 8.50 (5)   | 8.739 (7)       | 14.22                    |
| Hytech1100    | 8.13 (8)   | 17.531 (9)      | 28.52                    |
| Hytech2066    | 9.50 (4)   | 6.961 (6)       | 11.32                    |
| Hytech2031    | 10.5 (2)   | 9.850 (8)       | 16.02                    |
| Hudeiba2      | 8.38 (7)   | 4.184 (4)       | 6.81                     |
| Grand mean    | 9.13       |                 |                          |

Figures between brackets denote rank
†: Smaller value indicates better yield stability

**b) Eberhart and Russell’s Stability Model**

Table 5 shows the ANOVA from Eberhart-Russell Regression Model for forage yield of nine maize genotypes tested across 8 environments. The analysis of variance revealed significant differences among genotypes for forage yield. The GxE (linear) was significant. Table 6 shows the parameters of yield stability for DMY of nine maize genotypes across 8 environments. The genotype Hytech2055 ranked top in
forage yield (10.8 t/ha), showed the closest regression coefficient to unity (bi=1.0309) and small deviation from regression (σ^2d=0.320). PAN12 ranked third in forage yield (10.3 t/ha), showed regression coefficient close to unity (bi=1.0736) and small deviation from regression (σ^2d=0.211). Hytech2031 ranked second in forage yield (10.5 t/ha) with regression coefficient well below unity (bi=0.7993) and exhibited the second largest deviation from regression (σ^2d=1.165). Hytech2066 showed above average yield, regression coefficient ranking second in closeness to unity and large deviation from regression.

Table 5: ANOVA from Eberthart and Russell’s stability model for dry matter yield (t/ha) of nine maize genotypes

| Source               | DF | MS  |
|----------------------|----|-----|
| Genotypes (G)        | 8  | 10.344** |
| Environment (E), + in G.x E. |63 | 7.573 |
| E. in linear        | 1  | 0.000 |
| G x E. (linear)     | 8  | 1.748* |
| Pooled deviation    | 54 | 0.879 |
| Residual            | 144| 0.166 |

*, ** = Significant and highly significant at 0.05 and 0.01 probability level, respectively

Table 6: Mean performance and stability parameter of maize genotypes evaluated across eight environments using Eberthart and Russell’s stability model

| Genotypes | Dry matter yield (t/ha) | Regression coefficient (bi) | Deviation from linearity of regression (σ^2d) |
|-----------|-------------------------|-----------------------------|---------------------------------------------|
| PAN6966  | 8.38 (6)                | 1.1855 (5)                 | 0.521 (5)                                  |
| PAN12    | 10.3 (3)                | 1.0736 (3)                 | 0.211 (2)                                  |
| PAN14    | 7.75 (9)                | 1.1563 (4)                 | 0.266 (3)                                  |
| PAN6P-110| 8.50 (5)                | 0.7085 (9)                 | 0.636 (6)                                  |
| Hytech1100| 8.13 (8)              | 1.2724 (8)                 | 2.184 (9)                                  |
| Hytech2066| 9.50 (4)              | 0.9660 (2)                 | 0.985 (7)                                  |
| Hytech2031| 10.5 (2)               | 0.7993 (7)                 | 1.165 (8)                                  |
| Hytech2055| 10.8 (1)               | 1.0309 (1)                 | 0.320 (4)                                  |
| Hudeiba2 | 8.38 (7)                | 0.8075 (6)                 | 0.128 (1)                                  |
| Grand mean| 9.13                    |                             |                                             |

Figures between brackets denote rank

Table 7: Mean squares from AMMI stability model and the percentage of G x E explained by each IPCA+ for dry matter yield (t/ha) of nine maize genotypes grown in eight environments

| Source             | DF | SS    | MS    | F-value | Prob. > F | Variations explained (%) |
|--------------------|----|-------|-------|---------|-----------|--------------------------|
| Total              | 215| 1751.472|       |         |           | 100                      |
| Environments (E)   | 7  | 1246.958| 178.137**| 249.60  | 0.0000    | 71.2                     |
| Reps within E      | 16 | 11.419 | 0.714 |         | 0.65      |                          |
| Genotypes (G)      | 8  | 248.250| 31.031**| 9.42    | 0.0000    | 14.17                    |
| G x E              | 56 | 184.417| 3.293**| 6.98    | 0.0000    | 10.53                    |
| IPCA1              | 14 | 95.513 | 6.822 | 14.45   | 0.0000    | (51.79)                  |
| IPCA2              | 12 | 41.076 | 3.423 | 7.25    | 0.0000    | (22.27)                  |
| IPCA3              | 10 | 25.605 | 2.560 | 5.42    | 0.0000    | (13.88)                  |
| IPCA4              | 8  | 13.509 | 1.689 | 3.58    | 0.0009    | (7.33)                   |
| IPCA5              | 6  | 6.873  | 1.145 | 2.43    | 0.0296    | (3.73)                   |

c) AMMI Stability model

The mean squares from AMMI analysis of variance (Table 7) indicated significant variations among the genotypes, the environments and their interaction for forage yield. The GxE is highly significant accounting for 10.53% of the sum of squares. The genotype x environment interaction (GxE) was partitioned into seven interaction principal component analysis axis (IPCA). The IPCA1 and IPCA2 scores are highly significant explaining 51.79% and 22.27% of the variability relating to GxE, respectively (totaling 74.1%). Table 8 shows the IPCA axis scores and forage yield for nine maize genotypes averaged across 8 environments. Hytech2055, the highest yielding genotype scored the second lowest value in IPCA1 (0.2686) and the lowest value in IPCA2 (0.3191). The genotype PAN12 that ranked third in forage yield scored the lowest value in IPCA1 (-0.0726) coupled with high value in IPCA2 (-0.7807). Hytech2031, the second highest yielding genotype scored the second highest value in IPCA1 (0.9609) and IPCA2 (0.8561).
### Table 8: IPCA† scores and mean performance in dry matter yield (DMY) of nine maize genotype

| Genotypes  | DMY (t/ha) | IPCA1      | IPCA2       |
|------------|------------|------------|-------------|
| PAN6966    | 8.38 (6)   | -0.4460 (4) | -0.9833     |
| PAN12      | 10.3 (3)   | -0.0726 (1) | -0.7807     |
| PAN14      | 7.75 (9)   | 0.3278 (3)  | -0.5303     |
| PAN6P-110  | 8.50 (5)   | 0.8789 (7)  | -0.4147     |
| Hytech1100 | 8.13 (8)   | -1.6497 (9) | 0.5641      |
| Hytech2066 | 9.50 (4)   | -0.7686 (6) | 0.3310      |
| Hytech2031 | 10.5 (2)   | 0.9609 (8)  | 0.8561      |
| Hytech2055 | 10.8 (1)   | 0.2686 (2)  | 0.3191      |
| Hudeiba2   | 8.38 (7)   | 0.5007 (5)  | 0.6388      |
| Grand mean | 9.13       |             |             |

†: IPCA = Interaction principal component analysis axis
Figures between brackets denote rank

**Comparison of yield stability ranking in the different models**

Table 9 shows forage yield and stability ranking in 3 stability models for nine maize genotypes. As could be noticed in this table there were no major changes in stability ranking for the 9 maize genotypes across the 3 stability model. Hudeiba2 might be one of the exceptions ranking first in Eberhart and Russel’s model, fourth and fifth in Ecovalance and AMMI models, respectively. PAN12, the third-highest yielding genotype averaged the lowest rank across the 3 stability models. Hytech2055, the highest yielding genotype ranked third in average stability ranking. Hytech2031, the second-highest yielding genotype averaged the second highest stability rank across the 3 models.

### Table 9: Dry matter yield (DMY) and average stability ranking of maize genotypes tested across eight environments

| Genotypes  | DMY (t/ha) | Wricke (wi) -ecovalance | Eberhart & Russel’s (deviation σ²d) | AMMI (IPCA1) scores | Average stability rank |
|------------|------------|-------------------------|-------------------------------------|---------------------|------------------------|
| PAN6966    | 8.38 (6)   | 5.253 (5)               | 0.521 (5)                           | -0.4460 (4)         | 4.7                    |
| PAN12      | 10.3 (3)   | 3.475 (3)               | 0.211 (2)                           | -0.0726 (1)         | 2                      |
| PAN14      | 7.75 (9)   | 2.517 (1)               | 0.266 (3)                           | 0.3278 (3)          | 2.3                    |
| PAN6P-110  | 8.50 (5)   | 8.739 (7)               | 0.636 (6)                           | 0.8789 (7)          | 6.7                    |
| Hytech1100 | 8.13 (8)   | 17.531 (9)              | 2.184 (9)                           | -1.6497 (9)         | 9                      |
| Hytech2066 | 9.50 (4)   | 6.961 (6)               | 0.985 (7)                           | -0.7686 (6)         | 6.3                    |
| Hytech2031 | 10.5 (2)   | 9.850 (8)               | 1.165 (8)                           | 0.9609 (8)          | 8                      |
| Hytech2055 | 10.8 (1)   | 2.961 (2)               | 0.320 (4)                           | 0.2686 (2)          | 2.7                    |
| Hudeiba2   | 8.38 (7)   | 4.184 (4)               | 0.128 (1)                           | 0.5007 (5)          | 3.3                    |
| Grand mean | 9.13       |                         |                                     |                     |                        |

Figures between brackets denote rank

V. DISCUSSION

The highly significant genotype x environment interaction (GxE) validates the performing of stability analysis to know the contribution of each genotype to GxE which is the basic cause for differences between genotypes in their yield stability [10]. In the present study, the maize genotypes were studied under eight environment representing stress conditions resulting from the main effects of heat, salt, water and their interactions. Thus, the assessment of genotypes for yield stability should be considered within the context of the studied environments. We think that the test environments used in this study are appropriate since maize was evaluated as a forage crop assumed to have less demands of input and capable to flourish under marginal environments.
No one biometrical model can adequately explain the stability performance of genotype across environment [11]. In this study, three models with different statistical approaches were used to avoid limitations arising from using a single model. In Wricke’s Ecomulence model the cultivars with the lowest value contributed the least to the GxE interaction and are therefore more stable. Based on yield level and Ecomulence value the hybrid Hytech2055 can be regarded as the most stable as it ranked top in forage yield with the second lowest Ecomulence value. Similar conclusions were reported regarding the grain yield stability of the hybrid Hytech2055 [12]. The hybrid PAN12 came second in yield stability ranking third in forage yield coupled with the third lowest Ecomulence value. Hytech2031, though ranked the second top in forage yield failed to demonstrate good yield stability showing the second largest Ecomulence value.

In Eberhart and Russell model [5], two statistics were employed, namely: the regression coefficient as a measure of response [4] and deviation from linearity of regression [5] as stability measure. Results based on this model and similar techniques may be misleading if the genotype response over environment is not linear [6]. However, in this study the linearity of GxE is highly significant, validating the results obtained from Eberhart and Russell’s model. Mean yield of entries across all environments and regression coefficients are important indicators of cultivar adaptation [4]. A regression coefficient approximating 1.0 indicated average stability, and in association with high yield, the entry possesses general adaptability. However, entries with a low yield would be poorly adapted to the environment. Regression coefficient values increasing above 1.0 describe genotypes with increasing sensitivity to environmental change, thus below average stability. Regression coefficients decreasing below 1.0 provide a measure of greater resistance to environmental change, thus above average stability. However, regression coefficients must also be associated and interpreted with genotype mean yields to determine adaptability. In addition to the regression coefficient, Eberhart and Russell [5] added deviation from the regression as a measure of stability, where an entry would be considered stable with a deviation close to zero. Thus, based on the results of this study, the hybrid Hytech2055 exhibited the best general adaptability ranking top in forage yield with the least regression coefficient value. It showed moderate stability value ranking fourth in the deviation from the linearity of regression. The hybrids PAN12 and Hytech2066 came second in general adaptability, however, the former showed good stability parameter ranking the second-lowest in the deviation from linearity. The hybrid Hytech2031 though ranking second in forage yield, however, its regression coefficient value was well below unity suggesting greater resistance to environmental change, and therefore increasing specificity of adaptability to low-yielding environments. This was in conformity with the best yield obtained by this hybrid under full stress level. Therefore, Hytech2031 could have the relative advantage over the studied cultivars for forage production under the salt affected areas. Similar conclusions were reported for the adaptability of the hybrid Hytech2031 to low-yielding environments [12].

The Additive Main effects and Multiplicative Interaction method (AMMI) employs the ANOVA procedure and Principle Component Analysis (PCA) to extract a new set of coordinate axes (IPCA) which account more effectively for the interaction patterns [13]. The more the IPCA scores approach zero, the more stable the genotype is overall the environments sampled. Using PCA, the GxE was decomposed into 7 IPCAs two of them (IPCA1 and IPCA2) explained 74% of GxE variations into pattern-rich model. The variability relating to IPCA3 through IPCA5, though significant was small, therefore regarded as part of the residual. Based on the first two IPCAs, the hybrid Hytech2055 exhibited the best stability score followed by PAN12. The high yielding hybrid Hytech2031 showed considerably high scores in both IPCAs pointing to its adaptability to specific environments. As previously discussed Hytech2031 showed specific adaptation to the low yielding environment based on the Eberhart and Russell’s stability model. In fact, AMMI model is more powerful in detecting the environments to which genotypes are adapted by employing Biplot analysis [6]. However, this feature of AMMI analysis was not used in this study.

The study revealed that there were no major differences between the results obtained from the stability models used in this study. The average rank of genotypes based on the 3 stability models was more or less similar to that obtained for each model. Such conformity gives more reliability to the results obtained.

VI. Summary and Conclusion

The study revealed maize hybrids having broad and specific responses to the studied environments. Yield stability could be better investigated if the varieties are purposely subjected to major factors known to affect yield in a given domain. We recommend using different stability models to avoid limitations arising from using a single model.

Conflict of Interest

The authors declare that there is no conflict of interest.

References Références Referencias

1. D. P. Chaudhary, A. Kumar, S. S. Mandhania, P. Srivastava R. S. Kumar, Maize as fodder; an alternative approach, Directorate of Maize Research, Pusa Campus, New Delhi -110 012, Technical Bulletin. 2012/04 (2012) 32 p.
2. M. Koutsika- Sotiriou, Hybrid seed production in maize, In: Basra, A. S. (Ed.), Heterosis and hybrid seed production in agronomic crops, Food Products Press, NewYork. (1999) 25-64.
3. G. Wricke, On a method of understanding the biological diversity in field research. Z. Pfl.-Zücht. 47(1962) 92–146.
4. K.W. Finlay, G. N. Wilkinson, The analysis of adaptation in plant breeding program. Aust. J. Agric. Res. 14(1963) 742-754.
5. S. A. Eberhart, W. A. Russell, Stability parameters for comparing varieties. Crop Science. 6 (1966) 36-40.
6. J. Crossa, Statistical analysis of multi-location trials. In: Advances in Agronomy, Academic Press, Inc. 44 (1990) 55-85.
7. W. G. Cochran, G. M. Cox, Experimental designs. 2nd edn. John Wiley and Sons, Inc, New York. (1957) 293-316.
8. H. G. Gauch, R. W. Zobel, AMMI analysis of yield trials. In: Genotype-by-Environment Interaction Eds., Kang, M. S. and H. G. Jr. Gauch. CRC Press, Boca Raton, Florida. (1996) 85-122.

Appendix I: Chemical and physical soil properties of the experimental site at Shambat

| Depth (cm) | Chemical properties | Physical properties |
|------------|---------------------|---------------------|
|            | pH | EC (dS/m) | Na (mmol+) | SAR | Clay (%) | Silt (%) | Sand (%) |
| 0-15       | 7.79 | 1.4 | 5.1 | 2.4 | 42.1 | 15.9 | 42.0 |
| 15-35      | 7.88 | 1.0 | 4.3 | 2.5 | 39.6 | 15.8 | 44.6 |
| 35-51      | 7.87 | 1.2 | 7.1 | 4.5 | 44.1 | 16.4 | 39.5 |
| 51-75      | 7.91 | 2.0 | 12.5 | 6.3 | 51.4 | 16.6 | 32.0 |
| 75-120     | 7.71 | 2.2 | 16.0 | 9.2 | 50.0 | 16.6 | 33.4 |

Appendix II: Chemical soil properties of the experimental site at Soba

| Depth | pH paste | pH 1:5 | EC dS/m | SAR | ESP |
|-------|---------|-------|--------|-----|-----|
| 0-30  | 8.1     | 8.8   | 14.0   | 23.0 | 27.0 |
| 30-60 | 8.3     | 8.9   | 12.0   | 16.0 | 24.0 |

Soluble Cations and Anions Saturation Extract (meq/L)

|          | Na  | Ca  | Mg  | Cl  | CaCo3 | HCo3 |
|----------|-----|-----|-----|-----|-------|------|
| 0-30     | 10.3| 32.5| 6.0 | 8.3 | 0.0   | 4.6  |
| 30-60    | 19.0| 32.5| 6.5 | 6.3 | 0.0   | 4.3  |

Exchangeable Bases (Meq/100g)

|          | Na  | K   | CEC | N(%) | C/N% | Available P (ppm) |
|----------|-----|-----|-----|------|------|-------------------|
| 0-30     | 10.94 | 0.94 | 40  | 0.421| 0.037| 5.0              |
| 30-60    | 6.83  | 1.04 | 28  | 0.468| 0.042| 3.8              |

Source: Soil survey and land evaluation report. Land and Water Research Centre.ARC. Wad Medani. Sudan.
### Appendix III: Physical soil properties of the experimental site at Soba

| Depth (cm) | Mechanical analysis | Soil moisture | H₂O (Cm/cm) |
|------------|---------------------|---------------|-------------|
|            | Cs  | Fs  | Si  | C   | ½ bar | 15 bar | AWC | Vol% | Soil | Horizon |
| 0-20       | 8   | 18  | 37  | 37  | 27.2  | 13.6   | 13.6 | 22.0 | 0.33 | 6.6     |
| 20-50      | 4   | 30  | 21  | 45  | 28.9  | 15.5   | 13.4 | 21.8 | 0.22 | 6.6     |
| 50-80      | 7   | 17  | 33  | 43  | 28.5  | 15.3   | 13.2 | 22.8 | 0.23 | 6.9     |
| 80-120     | 4   | 23  | 33  | 40  | 27.1  | 14.6   | 12.5 | 20.8 | 0.21 | 8.4     |
| 120-160    | 5   | 20  | 29  | 46  | 36.1  | 19.0   | 17.1 | 30.4 | 0.30 | 12.0    |

Source: Soil survey and land evaluation report. Land and Water Research Centre, ARC. Wad Medani, Sudan.

### Appendix IV: Monthly mean temperature (°C), rainfall and relative humidity (R.H %) during the winter season (2013/2014).

| Month              | Mean Temperature | R.H. (%) | Total rain fall (mm) |
|--------------------|------------------|----------|----------------------|
| November 2013      | 34.0             | 20.0     | 27                   | 0.0     |
| December           | 32.0             | 16.0     | 32                   | 0.0     |
| January 2014       | 32.0             | 15.0     | 35                   | 0.0     |
| February           | 33.0             | 16.0     | 27                   | 0.0     |
| March              | 38.0             | 20.0     | 23                   | 0.0     |

Source: Meteorological Authority, Ministry of Environment Forestry and Physical Development (2014) Khartoum, Sudan.

### Appendix V: Monthly mean temperature (°C), rainfall and relative humidity (R.H %) during the summer season (2014).

| Month | Mean Temperature | R.H. (%) | Total rain fall (mm) |
|-------|------------------|----------|----------------------|
| Max.  | Min.             |          |                      |
| April | 40.9             | 27.4     | 16                   | Trace   |
| May   | 41.0             | 28.4     | 17                   | 4.6     |
| June  | 42.0             | 25.0     | 21                   | 0.6     |
| July  | 36.9             | 26.1     | 45                   | 73.6    |

Source: Meteorological Authority, Ministry of Environment Forestry and Physical Development (2014) Khartoum, Sudan.