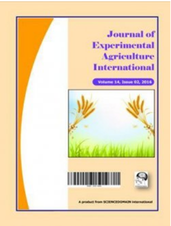

Journal of Experimental Agriculture International

21(1): 1-18, 2018; Article no.JEAI.24311
ISSN: 2457-0591
(Past name: American Journal of Experimental Agriculture, Past ISSN: 2231-0606)

Evaluation of Genotype x Environment Interaction and Stability of Grain Yield and Related Yield Components in Pearl Millet (*Pennisetum glaucum* (L.) R.Br.)

N. Lagat[1], P. Kimurto[2*], O. Kiplagat[1], B. K. Towett[2], L. Jeptanui[2], I. Gatongi[2], N. Njogu[2], H. Ojulong[3], E. Manyasa[3] and Siambi[3]

[1]Department of Biotechnology, University of Eldoret, Eldoret, Kenya.
[2]Department of Crop, Horticulture and Soils Science, Egerton University, Njoro, Kenya.
[3]International Crops Research Institute for the Semi Arid Tropics, Nairobi, Kenya.

Authors' contributions

This work was carried out in collaboration between all authors. Author NL conducted the trials. Author PK conducted the trials, did data analysis and reviewed and submitted the paper and main author. Authors OK and NN reviewed the paper. Author BKT collected data and managed the trial. Author LJ did the data analysis and field data collection. Author IG managed the data analysis. Authors HO and EM reviewed the paper and provided germplasm for evaluation. Author Siambi supported funding of field work and reviewed the paper. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JEAI/2018/24311
Editor(s):
(1) Dalong Guo, Professor, College of Forestry, Henan University of Science and Technology, Luoyang, People's Republic of China.
Reviewers:
(1) Enver Kendal, Kızıltepe Training Vocational High School, Mardin Artuklu University, Turkey.
(2) Desalegn Serba, Kansas State University, USA.
(3) Clint Magill, Texas A&M University, College Station, USA.
(4) Fábio Oliveira Diniz, Federal Institute of Education, Science and Technology of Piaui, Brazil.
Complete Peer review History: http://www.sciencedomain.org/review-history/23458

Original Research Article

Received 16th January 2016
Accepted 27th September 2017
Published 5th March 2018

ABSTRACT

Thirty six pearl millet genotypes were evaluated in randomized complete block design with two replications during 2011/2012 at two locations to study the magnitude of genotype by environment interaction for yield and yield related traits and identify the most stable high yielding genotypes. ANOVA of data at individual locations revealed significant differences among genotypes at Marigat and Koibatek for all yield components. Combined mean analysis of variance showed that the

---

**Corresponding author: E-mail: kimurtopk@gmail.com, Pkimurto@egerton.ac.ke;*

Genotype and location main effects and the genotype by environment interaction were highly significant (P≤0.01) for grain yield and other traits, indicating differential response of genotypes across testing locations and the need for stability analysis. Marigat was the most suitable environment and gave highest mean grain yield of 3620 kg/ha. The lowest yield 870 Kg/ha was recorded at Koibatek. Genotypes EUP 32, EUP 35, EUP 19 and EUP 10 produced high mean yield of 3530, 3080, 2690 and 2590 kg/ha respectively. The lowest grain 1290 kg/ha was obtained from genotype EUP 4.Based on the parameters of stability, three stable (widely adapted) and high yielding genotypes (EUP 34, EUP 18, and EUP 9) were identified. They also out-yield the standard open pollinated variety (OPV) check, Kat PM2. Genotypes EUP 32 was the highest yielding across all sites followed by EUP 35 and could be recommended for further multi-location evaluation in warmer environment and possible release for commercial production. The findings of this study showed that pearl millet hybrids have high potential for commercial production in Kenya than the OPVs. The ANOVA results showed that the effects of environments, genotypes and genotype x environment interaction (GE) were important in trait expression and performance of genotypes. In addition, it was observed that amount of rainfall received at both vegetative and post-anthesis phases and temperature had an effect on grain yield. The GGE biplot analysis characterised the environments in terms of stability and productivity, where Marigat was the best for grain yield; implying that environment-specific selection should be adopted. Genotypes EUP 34, EUP 18, and EUP 9 were the best performing since they out yielded the standard OPV check. These stable high yielding genotypes can be evaluated further in varied agro-ecologies and recommended for release as commercial hybrid varieties in ASALs of Kenya.

Keywords: Genotype by environment interaction; stability; pearl millet; yield.

1. INTRODUCTION

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is one of the world's hardiest warm season cereal crops grown in the tropical and sub-tropical regions of the world. Its is adapted to environmentally marginalised conditions worldwide [1] and a multipurpose [2] cereal for people living in semi-arid areas in East Africa [3]. It is ranked second among stable foods in east and central Africa [4]. Like sorghum, pearl millet is a crop of hot and dry climates, and can be grown in areas where rainfall is not sufficient (250-600 mm) for other cereal crops. In Kenya, the total area under pearl millets is about 93,310 ha, producing about 68,800 tons per annum with productivity of 200-800 Kg ha^{-1} against yield potential of 1500-3000 Kg ha^{-1}. Pearl millet is, however, especially important in south eastern Kenya comprising mainly Tharaka, Mbeere, Mwingi, Kitui, Makueni and also drier areas of the Rift Valley, mainly in Baringo, Elgeyo Marakwet and West Pokot. The eastern provinces are the main producer of millet, producing over 60% of the total millet while Rift valley produces less than 10% [5]. Several types of millet exist in production in different parts of the world. Statistics indicate that over 50% of the total millet grain production is pearl millet, 30% proso/golden and fox tail, millet and constitute approximately 11% finger millet. The remaining 8 species are of little economic importance and account for only 10% of the world millet production [6]. The widespread impression that pearl millet grain is essentially an animal feed, unpalatable to all but the desperately hungry, is wrong. The grain is actually a superior foodstuff, containing high quality protein with a good balance of amino acids. It has more oil than maize and is a "high-energy" cereal. Pearl millet is also a versatile foodstuff since it has neither the tannins nor the other compounds that reduce digestibility found in sorghum. Non-alcoholic beverages and snacks can be made and grain from certain cultivars is roasted whole and consumed directly. Moreover amongst all cereals (maize, sorghum, finger millet etc) pearl millet is the most nutritious with high levels of protein (up to 12%) and energy (3600 K cal kg-1). It has a cheap source of protein, grain iron (Fe) and zinc (Zn) [6]. The crop also forms an excellent feed for livestock both as grain and forage and thus advantageous as a dual purpose crop [7]. In addition, pearl millet is easy to grow and suffers less from diseases as compared to sorghum, maize, or other grains.

Despite the several advantages, on-farm productivity of pearl millet in many areas of semi-arid tropics is low partly due to the effect of several abiotic (rusts, insect pest) and biotic (drought, low soil fertility etc) constraints [8]. The economical approach to control this constraints is through resistance breeding [9] and selecting genotypes adapted to low input and drought-prone environments [10,11]. Unfortunately, the potential performance of improved genotypes under marginal conditions is always affected by the effect of genotype by environment interaction (GE) [12]. These lead to selection of genotypes not suitable for particular environments [13] and subsequently leading to low yield. It is therefore important to assess GE effect before releasing varieties [14,15].

Yield performance in crops, the observed phenotype, is a function of genotype, environment and genotype by environment interaction. Genotype by environment interaction is commonly observed as differential rank of cultivar performances among locations. Genotype by environment interaction is evaluated when different genotypes respond differently to diverse environments. Scientist have long been aware of the various outcomes of genotype by environment interaction in breeding programs. Genotype by environment interaction is important when it is significant and causes significant change in genotype ranks in different environments. A significant genotype by environment interaction can seriously impair efforts to select superior genotypes for crop introductions and cultivar development programs [12]. Yield is a dependent character resulting from interplay of various related traits. It is influenced by the growing environment and its heritability can be low. As a result, direct selection for yield has low efficiency in improving productivity of the crop. Knowledge of degree of association existing between yield as well as its yield components is very important for selection. This assumes greater importance in pearl millet because grains are formed in panicle and unless association between plant characters and yield are established, it may not be possible to identify yield components prior to harvest.

For successful selection, it is necessary to study the nature of association of characters with other relevant traits. Hence several methods have been adopted to assess GE in pearl millet breeding [16]. In this study the GGE-biplot analysis was used because of the ability to graphically better explain the genotype and genotype by environment components of variation and being more efficient in discriminating genotypes and environments [17,16].

Also, Path coefficient analysis provides a better means for selection by resolving the correlation coefficients of yield and its components into direct and indirect effects. Principal components analysis (PCA) is a multivariate analysis tool used to study the kind of variation present in a selected population (Toker, 2004) and multivariate polymorphism (Mallikarjuna et al., 2003). The first principal component and the second principal component normally account for the first and second highest amount of variance among the measurements taken, and so on (Broschat, 1979). Principal component analysis across the trials in millet using data that was pooled across three environments indicated that only four principal components were significant [18]. According to Khairwal et al. [18] eigen values greater than 1 are considered significant and component loadings greater than ± 0.3 are deemed meaningful. Their findings showed that, only the first four principal components were used for the study and traits with loadings greater than ±0.3 were taken to represent the corresponding principal axis. Similar results were obtained by Kiprotich et al. [19] when they analyzed 60 pearl millet genotypes for their biochemical composition. In this study 4 PCs accounted for a total variation of 81% with PC 1 accounting for 27.7% and PC 2 accounting for 19.1%. PC 3 accounted for 18.5 and the 4th PC accounting for 15.6%. These results were similar to Wedajo (2014) who found four principal components with the first PC closely associated with days to maturity, days to 50% flowering and days to 50% maturity when he evaluated 16 pearl millet genotypes. These indicated that; number of reproductive tillers and plant height and panicle characteristics are important traits to be considered in breeding for grain yield.

Furthermore the importance of evaluating many potential genotypes in different environments (location and seasons) before selecting desirable ones for release and commercial cultivation has been recognized by breeders [14]. An ideal cultivar is one that constantly yields well in its area of initial selection as well as other new sites [14]. The objectives of this study were to determine genotype by environment interaction for yield and yield traits in selected pearl millet genotypes and their yield stability across varied agro-zones.

2. MATERIALS AND METHODS

2.1 Experimental Sites

The study area (Marigat and Koibatek) are characterized as hot to warm semi-arid lowlands in which the major crops are finger millet and sorghum. The experiment was conducted at two locations, (Marigat and Koibatek) in Baringo County during the 2011/12 cropping season. These locations are found within altitudinal ranges of 1500-1890 m.a.s.l and are in the range of environments suitable for pearl millet growth. Since these locations are different in soil type, altitude, mean annual temperature and rainfall, each was considered as an individual environment. Description of the study locations is given in Table 1.

2.2 Experimental Materials (Genotypes)

Thirty five genotypes of hybrid pearl millet obtained from International Centre for Research in Semi-arid Tropics (ICRISAT), Nairobi were used in this study. An open pollinated (OPV) variety (Kat PM1) a released variety in Kenya was used as check. The description of the genotypes included in the experiment is given in Table 2.

2.3 Experimental Design and Trial Management

The experiment was conducted in a randomized complete block design (RCBD) with two replications. The experiments were planted at different times due to difference in the starting of the rainfall seasons in the two locations; Marigat, was planted in March while Koibatek was planted in May.

Seeds of each genotype were planted at a rate of 40 kg /ha in a plot consisting of four rows each 2m long and 0.75m inter-row and 0.20 m intra-row spacing. Thinning was done four weeks after planting to obtain a uniform plant density. Other agronomic practices were carried as earlier described [20,21]. At Marigat supplementary furrow irrigation was given to allow uniform establishment because of low rainfall.

2.4 Data Collection

Five plants from two middle rows were used for data collection and harvested at maturity. Individual plant data as well as plot data were collected on different traits of pearl millet genotypes. Data recorded on individual plant were plant height (cm), total number of tillers per plant, number of productive tillers per plant, panicle length (cm) and weight of grain per head (g), 1000 seed weight (weight of 1000 seeds) and grain yield per hectare (tons ha^{-1}) as earlier described [22].

2.5 Statistical Analysis

2.5.1 Analysis of variance (ANOVA)

All data collected were subjected to ANOVA using Integrated Breeding Platform's Breeding Management System version 3.0 (IBP-BMS) [23] and GenStat for windows 14th edition introduction [24]. The treatment means were separated using LSD at $P \leq 0.05$ after checking for homogeneity of experimental error. The following model was used for ANOVA of data of individual location.

General Mathematical Model for Individual Site ANOVA:

$$y_{ijk} = \mu + \rho_i + \tau_j + \tau\rho_{ij} + \varepsilon_{ijkl}$$

(Montgomery, 2005)

Where

$y_{ijk} =$ The individual observation in each Plot;

μ = Overall mean

ρ_i = Complete effect of the block;

τ_j = the estimate of jth treatment (hybrid) effect.

ε_{ijkl} = Overall error effect to the ij observation.

General Mathematical Model for ANOVA across Environments:

$$y_{ijk} = \mu + \alpha_i + \rho(\alpha)_j + \tau\rho_{ik} + \varepsilon_{ijkl}$$

(Montgomery, 2005)

Where:

$y_{ijk} =$ The individual observation in each Plot;

μ =Overall mean for each variable,

α_i= estimate of the environmental effect;

$\rho(\alpha)_j$= estimate of the jth block effect in ith environment;

$\tau\rho_{ik}$= estimate of the kth hybrid or variety;

ε_{ijkl}= Overall error effect in relation to ijkl observation.

2.6 Stability Analysis

ANOVA was carried to assess the stability of genotypes across the two environments. Environment and replication were considered random, while genotype effects were fixed. The F- test was used to check the significance of the pearl millet hybrid and the environmental effects, as well as the genotype x environment (G x E) interactions. Genotype x genotype x environment

Table 1. Description of the experimental locations and their overall agro-climatic conditions

Location	Altitude	Rainfall (mm)	Mean temperature(^{o}c)	Soil type
Marigat	1500	500 mm	23 – 37°c	Heavy loam to sand
Koibatek	1890	800 mm	10 – 28°c	Light loam soils

Source: National Meteorological Department (KALRO Perkerra)

Table 2. List and descriptions of pearl millet genotypes studied at two locations in 2011/12

Entry	Source	Remarks	Stress tolerance level
KAT PM 2	KALRO	OPV Commercial Check	Highly resistant to drought
EUP 1	ICRISAT	Hybrid	Moderately resistant to drought
EUP 2	ICRISAT	Hybrid	Moderately resistant to drought
EUP 3	ICRISAT	Hybrid	Moderately resistant to drought
EUP 4	ICRISAT	Hybrid	Moderately resistant to drought
EUP 5	ICRISAT	Hybrid	Moderately resistant to drought
EUP 6	ICRISAT	Hybrid	Moderately resistant to drought
EUP 7	ICRISAT	Hybrid	Moderately resistant to drought
EUP 8	ICRISAT	Hybrid	Moderately resistant to drought
EUP 9	ICRISAT	Hybrid	Moderately resistant to drought
EUP 10	ICRISAT	Hybrid	Moderately resistant to drought
EUP 11	ICRISAT	Hybrid	Moderately resistant to drought
EUP 12	ICRISAT	Hybrid	Moderately resistant to drought
EUP 13	ICRISAT	Hybrid	Moderately resistant to drought
EUP 14	ICRISAT	Hybrid	Moderately resistant to drought
EUP 15	ICRISAT	Hybrid	Moderately resistant to drought
EUP 16	ICRISAT	Hybrid	Moderately resistant to drought
EUP 17	ICRISAT	Hybrid	Moderately resistant to drought
EUP 18	ICRISAT	Hybrid	Moderately resistant to drought
EUP 19	ICRISAT	Hybrid	Moderately resistant to drought
EUP 20	ICRISAT	Hybrid	Moderately resistant to drought
EUP 21	ICRISAT	Hybrid	Moderately resistant to drought
EUP 23	ICRISAT	Hybrid	Moderately resistant to drought
EUP 23	ICRISAT	Hybrid	Moderately resistant to drought
EUP 24	ICRISAT	Hybrid	Moderately resistant to drought
EUP 25	ICRISAT	Hybrid	Moderately resistant to drought
EUP 26	ICRISAT	Hybrid	Moderately resistant to drought
EUP 27	ICRISAT	Hybrid	Moderately resistant to drought
EUP 28	ICRISAT	Hybrid	Moderately resistant to drought
EUP 29	ICRISAT	Hybrid	Moderately resistant to drought
EUP 30	ICRISAT	Hybrid	Moderately resistant to drought
EUP 3	ICRISAT	Hybrid	Moderately resistant to drought
EUP 32	ICRISAT	Hybrid	Moderately resistant to drought
EUP 33	ICRISAT	Hybrid	Moderately resistant to drought
EUP 34	ICRISAT	Hybrid	Moderately resistant to drought
EUP 35	ICRISAT	Hybrid	Moderately resistant to drought

Key: ICRISAT-International Centre for Research in semi-Arid tropics

(GGE) biplot analysis [25] was done to determine stability and pattern of response of genotypes in the test site using the first two principal components (PC1 and PC2) that were derived from subjecting environment to singular value decomposition.

3. RESULTS AND DISCUSSION

3.1 Effects of GXE in Both Sites Combined

Combined analysis of variance for both sites for grain yield showed that the effects of locations and genotypes were significant for all the measured traits (Tables 3 and 4). The combined mean showed effects of locations and genotypes were significant for all 8 traits (Tables 3 and 4). Mean performance over locations for genotypes for all measured traits is presented in Table 5. The significant effect of locations is due to variation in rainfall amount and seasonal distribution, temperature and soil type (Table 1). Therefore environments played a significant role in the expression of these traits among the cultivars.

Analysis of variance for data of individual environment and combined environments for most of the measured traits: total number of tillers (number of tillers), number of reproductive tillers (NRT), grain yield (GY), plant height (PH), panicle length (PL) and grain yield (t ha^{-1}) showed that there was significant difference amongst the cultivars for most traits (Tables 3 and 4).

The mean grain yields at individual locations (Table 4) ranged from 3600 kg/ha at Marigat to 800 kg/ha at Koibatek. Despite the high rainfall, Koibatek gave lowest yield of 800 kg/ha. Results further showed that generally the coefficients of determination were low (R^2 =0.29-0.34) for the most traits. This is a clear indicator that a greater variation was due to the environmental effect. This observation was is corroborated by the rainfall pattern variation observed in each environment (Fig. 1). The performance of environments was influenced by the rainfall amount received where the best performing environments in terms of grain yield and yield components received lower rainfall amounts during the growing season. Due to additional effects of slow crop growth due to low temperature, the poor performing environment of Koibatek, received most rainfall was during the flowering phase while the best performing environments (Marigat), received most rainfall during the vegetative phase. A probable reason why the Koibatek environment performed poorly in terms of grain yield when rainfall is received during flowering, is the possibility that there is disruption of the pollination process since the pearl millet is predominantly out-crossing, with support by wind. Similar findings have been reported [20] where it was noted that heavy rainfall during flowering also causes reduced seed set and poor grain quality, in addition to promoting rust and consequently low grain yield. In addition, Gebre [26] reported that rainfall pattern is one of the factors that he noted as being a major source of variable performance of improved genotypes (hybrids and OPVs as case in this study). The environments being important in genotype performance has also been reported in several pearl millet studies [27,28,29,15].

Furthermore, the differences in the mean temperatures in the two locations (Table 1) could have affected developmental processes such as leaf and spikelet initiation and tillering, dry matter produced, and both biological and economic. Similar findings were reported by Chin and Monteith [30] who noted that ggermination rate of pearl millet cv. BK 560 increased linearly with temperature from a base of 10-12°C to a sharply

Table 3. Mean squares for average grain yield of 36 pearl millet genotypes evaluated in Marigat and Koibatek in 2012/2013

Source of variation	D.F	Mean Square
Replication	2	16.49
Environment (E)	1	544.76***
Season	1	0.92
Genotype (G)	35	1.25*
Environment x Season	1	4.04*
Environment x Genotype	35	1.25*
Season x Genotype	35	0.04
Environment x Season x Genotype	35	0.04
Error	144	0.8

*Key: *, ** and *** = Significant at P ≤ 0.05,).01 and P ≤ 0.001, respectively*

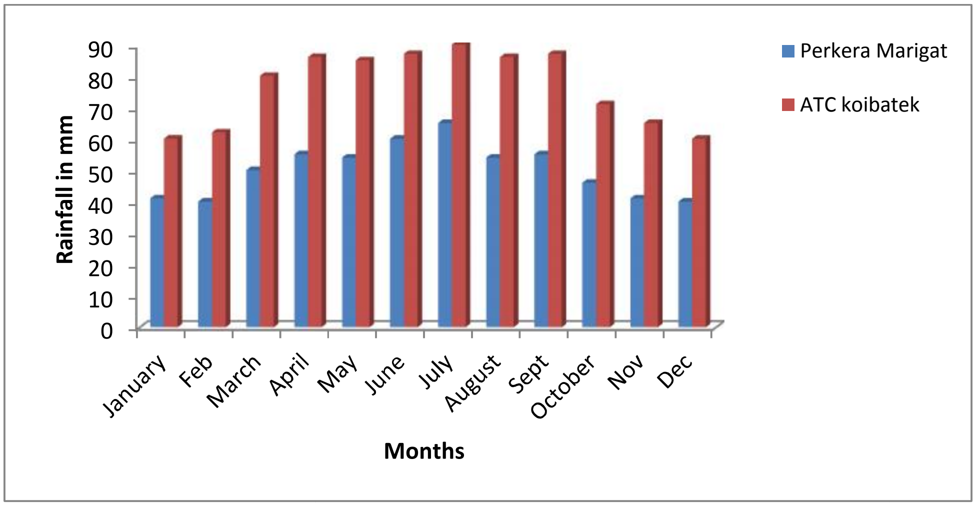

Fig. 1. Rainfall distribution in Koibatek and Marigat study sites in during the growing sesaon

defined optimum at 33-34°C and declined to zero at about 45-47°C. They also noted that other developmental processes such as leaf and spikelet initiation and tillering responded similarly to temperature. They noted that the amount of dry matter produced per unit of intercepted radiation appears to be conservative at about 2.4 g/MJ (+10%) for mean air temperatures ranging from 20 to 36°C. The highest yield, both biological and economic, was obtained at 22°C, mainly because the duration of cv. BK 560 was about 30 days longer at 22 than at 31°C.

ANOVA showed that there was significant differences in the yield and yield related traits of the test genotypes in both sites (Table 4). Reproductive tillers ranged from 45-87% as compared to the vegetative tillers indicating that there was high tiller abortions, especially in Marigat. Genotypes were 18% taller in Marigat than Koibatek averaging 1.94 m in Marigat as compared to 1.66 m in Koibatek (Table 4). In this study, plant height was significantly influenced by G x E nteraction. Similar findings were reported by Hakim (2006) who noted that plant height expressed their maximum genetic potential at different seasons in pearl millet evaluation under Mediterranean climate. This also showed that plant height could be used to fulfill farmers multipurpose requirements of fodder/hay and grain.

The panicle characteristics (length, weight, diameter) were upto 200 times greater in Marigat than Koibatek which explains why the grain yield were higher in Marigat than Koibatek. A significant variations among tested genotypes for the yield and related traits indicate the existence of variability among the test genotype, hence this promotes effective selection. Significant GxE interaction in the study indicate that phenotypic response to changes in the environment are not the same for all the genotypes. Similar findings were reported by Abdelrahman and Abdalla [31] in varied ecozones in Sudan. The best genotypes in one environment was not the best in another environment and that is why there was variation in genotype performance in the two sites (Tables 5 and 6).

The results of this study showed that genotypes EUP 32 and EUP 35 gave highest yield (6.21 and 5.32 Kgs/ha respectively) at Marigat as compared to 0.7 and 0.8 tons/ha respectively in Koibatek (Tables 4 and 5). These genotypes were recommended for further evaluation and possible release in lower ASALs of Marigat since they had double the yields than the current OPVs commercial checks (KAT PM2) which had a mean yield of 2800 kgs/ha. The findings of this study showed that pearl millet hybrids had high potential for commercial production in Kenyas ASALs than the OPVs.

The ANOVA adequately identified GE interaction as a significant source of variation but it is not able to explore the nature [32] of the GE interaction which may mask the true performance of genotypes in certain environments [16] and thus the need to explore more methods; for which case GGE biplot was adopted. Overall the variation in performance highlights the importance of environments in genotype performance and consequently GE interaction in trait expression.

3.2 Yield Stability Analysis of Grain Yield Response

Genotype by environment interaction continues to be challenging issue among plant breeders, geneticists, and agronomist who conduct crop performance trials across different environments. The ANOVA and stability analysis for yield showed that there was significant effect of environment x season x genotype of genotype performance (Table 3, Fig. 1). The genotype performance was expressed in terms of three parameters namely: mean yield of sites (XȲ), deviation from regression (S^2di) and standard error (SE). Standard error (SE) and the deviation from regression (S^2di) were calculated from mean grain yield (Table 6). A stable genotype is one with the smallest deviation interval S_2di= < 0 and lowest SE. According to these stability parameters, significant differences were noted for standard error (SE) and deviation from regression (S^2di).

The findings of this study showed that, the most stable genotypes were hybrids EUP 4 (S^2di=0.68) and EUP 24 (S^2di=1.28) and the check, Kat PM1 (S^2d=1.44) (Table 6). This is because they had standard deviation values that were not significantly different from 1 (S^2d=1=<1), thus displaying higher stability and adaptable to wider environments, even though they had low grain yield. In contrast genotypes EUP 32 and EUP 35 had highest mean standard deviation values that were significantly greater than 1 ((S^2d>2) (Table 6). This shows that they were only adapted to single environments, that are much warmer (like Marigat) and may not produce meaningful yield in colder environments like Koibatek. These genotypes however had highest yielding in Marigat and lowest in Koibatek, indicating high contribution to genotype by location interaction.

The other genotypes with good yield stability were EUP 22, EUP 33 and EUP 11 while those with low stability were EUP 19, EUP 23 and EUP 15 (Table 6). The other sixteen genotypes had average stability, hence they may be adapted to both environments. Such genotypes could be recommended for use in improvement of yield of less stable lines. The other fifteen genotypes that had below yield and also poorly adapted in all environments. These genotypes include EUP 11, EUP 13, EUP 14, EUP 16, EUP 2, amongst others.

The study illustrates that identification of hybrids with high grain stability and average stability is very important since stability parameters for grain yield of a single plant indicate linear and non-linear components of G × E. Similar findings were reported in rice [33].

3.3 GGE Biplot Analysis

GGE biplot analysis was used to determine stability and the best genotypes in various locations. The mean grain yield and two stability parameters viz., standard error and deviation from regression (S^2di) were obtained to access the superior genotype (Table 6 and Fig. 2). An ideal genotype is one that combines high yield and least deviation from regression. Genotype EUP 34, 14, 20, 27 and EUP 21 high yielding and stable in both environments. Similar findings were reported by Yan [34] who found three out of 16 ideal genotypes evaluated that that combined high yield and least deviation from regression across 4 sites under semi arid environment. Fig. 3 shows that Marigat was the ideal environment while Koibatek was desirable for discriminating for grain yield and other related traits. The two environments had similar discriminating ability and so either can be used for selecting best performers with minimal loss of information [35]. The genotype EUP 32 and EUP 7 were especially suitable for production at Marigat and Koibatek respectively and hence were the most ideal for grain yield. The line which passes through the origin and is perpendicular to the average environment axis with arrows represents the stability of genotypes. Either direction away from the biplot origin on this axis indicates greater genotype by environment interaction and reduced stability (Yan, 2002). Fig. 4 also indicates genotypes EUP 23, EUP1, EUP 9 performed poorly in both environments while EUP 32, EUP 29, EUP19 EUP 26 were highly stable in terms of grain yield and associated with the stable environments as compared to EUP 22, EUP7, EUP 10 who won in unstable environment and were also unstable. The high yielding genotypes were also moderately susceptible to drought and rust (unpolished data). In contrast, the stable and high yielding genotypes were different from those resistant to rust and drought (unpublished data). Similar findings were reported by Yadav and Duhan [8] who noted that high yielding genotypes were mostly susceptible to drought and rust in mid altitude areas.

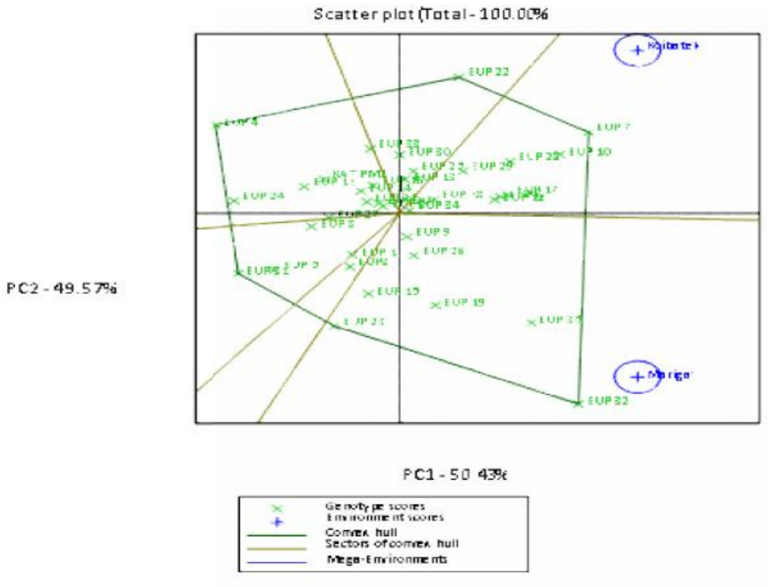

Fig. 2. The best genotypes base on genotype-by-environment interaction

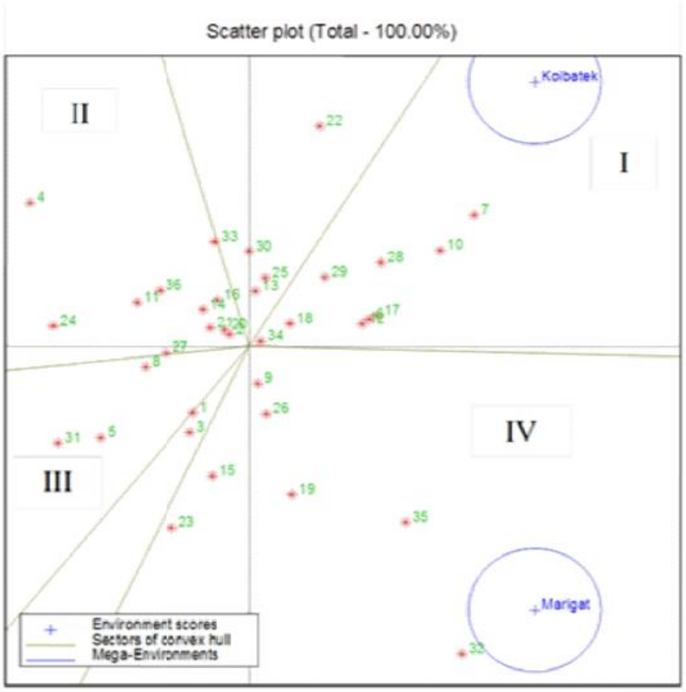

Fig. 3. Biplot for PCA 1 vs PCA 2 scores of different genotypes

These observations emphasize the importance of GE interaction and adopting selection for specific environments. Several authors Gupta et al., [29] and (2014) and Mashiri et al. [36] have used the GGE biplot to identify pearl millet mega environments to reduce number of test environments. In many other pearl millet studies, GGE biplot technique have been adopted to estimate environmental effects for days to flowering, plant height and physiological maturity [1]. In addition, Bashir et al. [1] used GGE analysis to identify the best performers for grain yield while Mustapha and Bakari [37] used it to identify stable genotypes with high grain yield. Therefore using the GGE biplot in selecting for stability and adaptability of genotypes for grain yield and other yield-related traits adds value to breeding programs and merits its use.

Table 4. Averages of yield related traits of 35 pearl millet hybrids and an OPV evaluated at Marigat and Koibatek, Kenya in 2012/2013 growing seasons

Entry	No. reproductive tillers	No. Vegetative tillers	Plant. Height(cm)	Panicle Length (cm)	Panicle weight(g)	Panicle diameter (cm)	1000 seed weight(g)	Yield t ha^{-1}
			Marigat					
KAT PM2	5.80	10.10	185.40	21.10	34.20	5.70	10.40	2.81
EUP 1	6.70	13.70	189.70	22.40	36.00	5.90	13.60	3.63
EUP 2	6.70	10.80	188.60	22.40	35.80	5.90	12.90	3.45
EUP3	6.80	13.30	178.00	22.80	36.00	5.90	13.70	3.75
EUP 4	5.20	9.80	177.30	19.90	32.30	5.30	8.80	1.73
EUP 5	6.50	13.40	185.10	22.20	35.50	5.90	12.90	3.32
EUP 6	7.20	14.50	206.10	22.80	36.90	6.20	14.50	4.03
EUP 7	6.90	14.60	205.20	22.00	36.50	6.10	13.80	4.03
EUP 8	6.00	11.00	181.80	21.30	35.00	5.70	11.40	3.22
EUP 9	6.90	14.30	185.50	23.00	36.40	6.10	13.80	3.80
EUP 10	7.00	13.40	206.40	22.50	36.70	6.20	14.20	4.00
EUP 11	5.70	11.60	184.40	21.00	34.10	5.70	10.10	2.80
EUP 12	7.00	14.40	206.60	23.10	36.70	6.20	14.20	4.00
EUP 13	6.40	12.90	203.60	22.20	35.50	5.90	12.90	3.30
EUP 14	5.80	13.60	187.50	21.40	34.90	5.70	11.40	3.20
EUP 15	7.40	14.70	183.70	24.10	37.10	6.20	14.70	4.10
EUP 16	6.10	13.30	189.40	21.70	35.10	5.70	11.70	3.20
EUP 17	7.30	14.60	207.40	23.80	36.90	6.20	14.60	4.00
EUP 18	6.60	13.90	188.60	22.40	35.70	5.90	12.90	3.70
EUP 19	7.50	14.30	208.80	24.30	37.50	6.30	15.40	4.60
EUP 20	6.40	13.60	187.10	22.40	35.30	5.90	12.70	3.40
EUP 21	6.30	14.40	187.90	22.20	35.30	5.90	12.40	3.30
EUP 22	5.70	11.90	183.50	20.90	33.90	5.40	9.00	2.80
EUP 23	7.40	13.20	208.10	24.20	37.20	6.30	15.20	4.10
EUP 24	5.60	9.80	182.20	20.80	33.40	5.30	9.00	2.50
EUP 25	6.20	14.30	185.10	22.20	35.20	5.80	12.30	3.30
EUP 26	7.00	14.10	206.20	23.10	36.60	6.10	13.90	4.05
EUP 27	6.10	14.10	198.90	21.90	35.10	5.80	12.40	3.22
EUP 28	6.90	14.10	199.60	21.50	36.10	6.00	13.80	3.81

Entry	No. reproductive tillers	No. Vegetative tillers	Plant. Height(cm)	Panicle Length (cm)	Panicle weight(g)	Panicle diameter (cm)	1000 seed weight(g)	Yield t ha^{-1}
EUP 29	6.80	14.10	198.60	22.90	36.00	5.90	13.70	3.62
EUP 30	5.70	14.10	188.10	21.20	34.50	5.70	11.00	3.13
EUP 31	5.70	11.10	183.60	21.30	34.60	5.70	11.90	3.14
EUP 32	7.80	15.20	209.40	25.40	37.70	6.10	17.20	6.21
EUP 33	5.70	10.10	186.30	21.20	34.40	5.70	10.90	2.92
EUP 34	6.60	13.60	189.40	22.30	35.60	5.90	12.90	3.61
EUP 35	7.70	14.90	209.10	24.50	37.50	6.30	16.40	5.32
P<0.05	*	*	**	*	*	*	**	**
Mean	6.5	13.2	194.3	22.4	36.2	6.01	12.9	3.6
C.V (%)	37.1	25.2	11.6	11.7	22.4	21.8	28.1	24.4
				Koibatek				
KAT PM2	10.30	13.90	180.70	17.60	10.80	2.50	9.20	0.80
EUP 1	9.60	15.00	138.30	16.70	9.40	2.30	8.20	0.70
EUP 2	11.00	12.90	174.80	18.10	11.20	2.60	9.80	0.80
EUP3	9.50	12.90	139.30	16.60	9.40	2.30	8.20	0.70
EUP 4	10.00	11.90	171.40	16.90	10.50	2.50	9.20	0.80
EUP 5	8.60	14.70	139.00	16.10	8.80	2.10	7.70	0.60
EUP 6	11.70	11.70	176.40	19.00	13.20	2.70	11.30	0.90
EUP 7	13.80	13.30	193.00	21.50	14.90	3.00	13.50	1.10
EUP 8	9.70	13.90	138.90	16.70	9.50	2.40	8.50	0.70
EUP 9	10.50	14.90	180.60	17.80	10.90	2.60	9.50	0.80
EUP 10	12.90	14.20	191.10	20.00	14.40	2.90	13.20	1.10
EUP 11	10.10	11.70	172.00	17.00	10.60	2.50	9.20	0.80
EUP 12	11.70	10.70	176.70	18.90	13.20	2.70	11.30	0.90
EUP 13	10.10	11.60	174.40	18.50	12.70	2.70	10.70	0.90
EUP 14	10.10	12.10	180.90	18.10	11.40	2.60	10.00	0.80
EUP 15	10.60	11.00	138.00	16.50	8.90	2.30	7.80	0.70
EUP 16	11.10	10.50	181.70	18.10	11.40	2.70	10.10	0.80
EUP 17	12.20	11.90	188.00	19.70	13.80	2.80	11.70	1.00
EUP 18	11.10	15.60	173.60	18.30	12.30	2.70	10.60	0.90
EUP 19	9.80	13.20	139.10	16.30	9.60	2.40	8.70	0.70
EUP 20	10.90	12.90	174.10	17.90	11.10	2.60	9.70	0.80
EUP 21	10.90	13.60	170.00	17.90	11.10	2.60	9.60	0.80

Entry	No. reproductive tillers	No. Vegetative tillers	Plant. Height(cm)	Panicle Length (cm)	Panicle weight(g)	Panicle diameter (cm)	1000 seed weight(g)	Yield t ha^{-1}
EUP 22	13.50	12.00	190.50	20.20	14.80	2.90	13.30	1.10
EUP 23	7.80	12.00	137.50	15.30	8.80	2.00	7.60	0.60
EUP 24	9.50	13.30	138.50	16.10	9.10	2.20	8.00	0.70
EUP 25	11.30	11.50	175.40	18.80	12.90	2.70	10.80	0.90
EUP 26	10.20	13.60	173.00	17.20	10.70	2.50	9.20	0.80
EUP 27	9.90	12.40	140.10	16.90	10.50	2.50	9.20	0.70
EUP 28	12.80	12.50	188.20	20.00	13.90	2.90	12.50	1.00
EUP 29	11.90	11.50	176.80	19.20	13.50	2.70	11.70	0.90
EUP 30	11.50	11.30	175.70	18.90	13.10	2.70	11.00	0.90
EUP 31	7.20	11.50	125.50	15.10	8.10	1.90	17.00	0.60
EUP 32	9.80	18.60	139.20	16.80	10.10	2.50	8.90	0.87
EUP 33	11.20	11.80	173.40	18.60	12.90	2.70	10.70	0.90
EUP 34	11.10	11.10	182.60	18.30	12.10	2.70	10.50	0.80
EUP 35	11.80	12.40	182.30	17.80	10.90	2.60	9.50	0.98
P<0.05	*	*	***	*	*	*	**	**
Grand mean	12.80	10.60	166.4	17.90	11.0	2.50	9.90	0.80
C.V (%)	27.20	18.60	13.00	15.40	14.6	18.1	16.6	19.5

*Key: *, ** and *** = Significant at $P \leq 0.05$,).01 and $P \leq 0.001$, respectively*

Table 5. Means of thirty five pearl millet hybrids along with an OPV tested for grain yield performance across two location in Kenya

Entry	No. Reproductive tillers	No. Vegetative tillers	Plant. Height(cm)	Panicle Length (cm)	Panicle weight(g)	Panicle diameter (cm)	1000 seed weight(g)	Yield t ha^{-1}
KAT PM2	9.85	10.20	183.05	31.90	4.10	4.10	9.80	1.80
EUP 1	10.85	11.65	164.00	31.80	4.10	4.10	10.90	2.15
EUP 2	9.80	10.90	181.70	33.60	4.25	4.25	11.35	2.10
EUP3	9.85	11.40	158.65	32.20	4.10	4.10	10.95	2.20
EUP 4	8.55	9.90	174.35	30.40	3.90	3.90	9.00	1.25
EUP 5	10.60	11.00	162.05	31.00	4.00	4.00	10.30	1.95
EUP 6	9.45	13.10	191.25	36.00	4.45	4.45	12.90	2.45
EUP 7	10.10	14.20	199.10	36.90	4.55	4.55	13.65	2.55
EUP 8	9.95	10.35	160.35	30.80	4.05	4.05	9.95	1.95
EUP 9	10.90	12.40	183.05	33.90	4.35	4.35	11.65	2.30
EUP 10	10.60	13.15	198.75	36.90	4.55	4.55	13.70	2.55
EUP 11	8.70	10.85	178.20	31.60	4.10	4.10	9.65	1.80
EUP 12	8.85	13.05	191.65	36.30	4.45	4.45	12.75	2.45
EUP 13	9.00	11.50	189.00	34.90	4.30	4.30	11.80	2.10
EUP 14	8.95	11.85	184.20	32.80	4.15	4.15	10.70	2.00
EUP 15	9.20	12.65	160.85	33.00	4.25	4.25	11.25	2.40
EUP 16	8.30	12.20	185.55	33.10	4.20	4.20	10.90	2.00
EUP 17	9.60	13.40	197.70	37.60	4.50	4.50	13.15	2.50
EUP 18	11.10	12.50	181.10	34.70	4.30	4.30	11.75	2.30
EUP 19	10.35	12.05	173.95	33.90	4.35	4.35	12.05	2.65
EUP 20	9.65	12.25	180.60	33.50	4.25	4.25	11.20	2.10
EUP 21	9.95	12.65	178.95	33.30	4.25	4.25	11.00	2.05
EUP 22	8.85	12.70	187.00	35.70	4.15	4.15	11.15	1.95
EUP 23	9.70	10.50	172.80	33.00	4.15	4.15	11.40	2.35
EUP 24	9.45	9.65	160.35	29.90	3.75	3.75	8.50	1.60
EUP 25	8.85	12.80	180.25	35.10	4.25	4.25	11.55	2.10
EUP 26	10.30	12.15	189.60	33.80	4.30	4.30	11.55	2.40
EUP 27	9.25	12.00	169.50	32.40	4.15	4.15	10.80	1.95
EUP 28	9.70	13.45	193.90	35.40	4.45	4.45	13.15	2.40
EUP 29	9.15	13.00	187.70	36.40	4.30	4.30	12.70	2.25
EUP 30	8.50	12.80	181.90	34.30	4.20	4.20	11.00	2.00

Entry	No. Reproductive tillers	No. Vegetative tillers	Plant. Height(cm)	Panicle Length (cm)	Panicle weight(g)	Panicle diameter (cm)	1000 seed weight(g)	Yield t ha^{-1}
EUP 31	8.60	9.15	154.55	29.40	3.80	3.80	14.45	1.85
EUP 32	13.20	12.50	174.30	35.50	4.30	4.30	13.05	3.45
EUP 33	8.75	10.65	179.85	34.10	4.20	4.20	10.80	1.90
EUP 34	8.85	12.35	186.00	34.40	4.30	4.30	11.70	2.20
EUP 35	10.05	13.35	195.70	35.40	4.45	4.45	12.95	3.05
P<0.05	*	*	**	*	ns	*	**	**
G. Mean	9.65	11.90	180.35	33.40	4.26	4.26	11.40	2.20
C.V (%)	32.15	21.90	12.30	26.30	19.95	19.95	22.35	21.9

*Key: *, ** and *** = Significant at P ≤ 0.05,).01 and P ≤ 0.001, respectively*

Table 6. Stability parameters (S^2di and SE) of grain yield across the two site for thirty six pearl millet genotypes tested

Genotype	Mean of sites (XY)	Koibatek	Marigat	(S^2d)	SE	Rank
Kat PM2	1.86	0.84	2.88	1.44	1.02	6
EUP1	2.22	0.76	3.67	2.07	1.46	24
EUP10	2.59	1.11	4.06	2.08	1.47	25
EUP11	1.82	0.81	2.83	1.43	1.01	5
EUP12	2.52	0.98	4.06	2.17	1.54	28
EUP13	2.14	0.92	3.36	1.72	1.22	13
EUP14	2.03	0.86	3.2	1.65	1.17	9
EUP15	2.42	0.72	4.12	2.4	1.70	32
EUP16	2.05	0.88	3.22	1.65	1.17	8
EUP17	2.54	1.00	4.09	2.19	1.56	30
EUP18	2.31	0.92	3.7	1.97	1.39	21
EUP19	2.69	0.77	4.61	2.72	1.92	34
EUP2	2.16	0.86	3.46	1.84	1.31	17
EUP20	2.13	0.86	3.41	1.8	1.28	15
EUP21	2.09	0.85	3.33	1.75	1.24	14
EUP22	1.96	1.12	2.81	1.2	0.85	2
EUP23	2.42	0.64	4.19	2.51	1.77	33
EUP24	1.63	0.72	2.54	1.28	0.91	3
EUP25	2.14	0.94	3.34	1.7	1.21	10

Genotype	Mean of sites (XY)	Koibatek	Marigat	(S^2d)	SE	Rank
EUP26	2.44	0.82	4.06	2.29	1.62	31
EUP27	2.02	0.79	3.24	1.73	1.22	11
EUP28	2.44	1.05	3.83	1.97	1.39	22
EUP29	2.31	0.99	3.63	1.86	1.32	18
EUP3	2.26	0.74	3.78	2.15	1.52	27
EUP30	2.03	0.95	3.12	1.54	1.09	7
EUP31	1.9	0.62	3.18	1.81	1.28	16
EUP32	3.53	0.77	6.29	3.91	2.76	36
EUP33	1.92	0.93	2.9	1.4	0.99	4
EUP34	2.27	0.88	3.65	1.96	1.39	20
EUP35	3.08	0.84	5.32	3.17	2.24	35
EUP4	1.29	0.81	1.78	0.69	0.49	1
EUP5	2.01	0.66	3.36	1.91	1.35	19
EUP6	2.53	0.99	4.07	2.18	1.54	29
EUP7	2.6	1.17	4.04	2.03	1.43	23
EUP8	1.99	0.76	3.21	1.73	1.23	12
EUP9	2.35	0.84	3.86	2.14	1.51	26
Grand Mean	**2.25**	**0.87**	**3.64**	**1.96**	**1.39**	

Key: S^2di-Standard deviation; SE-Standard error

3.4 Additive Main Effects

The extend of contribution of particular yield component to grain yield may not be evaluated only by correlation (Arulselvis et al., 2008), but also by using other statistical method such as principal component analysis (PCA) that explain further the contribution of other components. The additive main effects based on GGE showed that that the first and second interaction principal component axes (PCA 1 and PCA 2) were significant (Fig. 3) and accounted for 71.6% of total variation. The first principal component (PCA 1) accounted for 56.81% of the total variation and second principal component (PC2) 14.86% of the total genotype by environment interaction. The yield trait that had the highest variation and contributed to yield among the yield components was panicle length (PCA 1) with eigen values of 0.481 while the least variant in the yield component was vegetative tillers of with eigen values of 0.0001. The major variation in PCA 2 was contributed by being number of reproductive vegetative tillers (eigen value 0.071) and 1000 seed weight (0.47) with the least being panicle weight. The distribution of genotype points in the GGE biplot (Fig. 1) revealed that the genotypes, EUP 34, and EUP 9 were scattered close to the origin, indicating minimal interaction of these genotypes with locations. The remaining genotypes scattered away from the origin in the biplot indicating that the genotypes were more sensitive to environmental interactive forces. Interaction of genotypes with specific environmental conditions was judged by projection of genotype points on to environment. Accordingly EUP 32 and 35 had high interaction in Marigat and genotype EUP 7 had high interaction in Koibatek. The polygon view of the GGE biplot (Fig. 2) indicates the best genotype(s) in each environment and groups of environments (Hunt, 2002). The highest yielding genotype in location Marigat was EUP 32, in Koibatek the highest yielding genotypes was EUP 7. %. Similar findings were earlier reported (Wedajo, 2014) who found four principal components with the first PC closely associated with days to maturity, days to 50% flowering and days to 50% maturity. These indicated that the number of reproductive tillers, seed weight and plant height and panicle characteristics are important traits to be considered in breeding for grain yield.

4. CONCLUSION AND RECOMMENDATION

The findings of this study showed that pearl millet hybrids have high potential for commercial production in Kenya than the OPVs. Genotypes EUP 32 were the highest yielding across all sites followed by EUP 35 and could be recommended for further multi-location evaluation in warmer environment and possible release for commercial production. The study also focused on establishing the genotype by environment interaction effect, characterizing environments and genotypes. The ANOVA results showed that the effects of environments, genotypes and genotype x environment interaction (GE) were important in trait expression and performance of genotypes. In addition, it was observed that amount of rainfall received at both vegetative and post-anthesis phases and temperature had an effect on grain yield. The GGE biplot analysis was useful in concisely characterising the environments and the genotypes. It characterised the environments in terms of stability and productivity, where Marigat was the best for grain yield; implying that environment-specific selection should be adopted. The results on stability and wide adaptation showed that genotypes EUP 34, EUP 18, and EUP 9 were the best performing since they out yielded the standard OPV check. These stable high yielding genotypes can be evaluated further in varied agro-ecologies and recommended for release as commercial hybrid varieties in ASALs of Kenya.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Bashir EMA, Ali AM, Adam-Ali M, Ismail MI, Parzies HK, Haussmann BIG. Patterns of pearl millet genotype-by-environment interaction for yield performance and grain iron (Fe) and zinc (Zn) concentrations in Sudan. Field Crops Research. 2014;166: 82-91.
Available:https://doi.org/10.1016/j.fcr.2014.06.007
2. IFAD. Farmer participatory testing of technologies to increase sorghum and pearl millet production in the Sahel; 1999.
Available:http://www.ifad.org/grants

3. Lubadde G, Tongoona P, Derera J, Sibiya J. Major pearl millet diseases and their effects on on-farm grain yield in Uganda. African Journal of Agricultural Research. 2014;9(39):2911-2918.
4. Mgonja MA, Shiferwaw BK, Mitaru B. An assessment of sorghum and millet sub sector in ECA. Towards better integration and exploitation of productivity enhancement and market opportunities. *In* Proceedings of ECARSAM stakeholders workshop, Daresalaam, Tanzania, November 20-22; 2006.
5. Omamo SW, Xinshen D, Wood S, Chamberlin J, You L, Benin S, Ulrike WS, Tatwangire A. Strategic priorities for agricultural development in Eastern and Central Africa Pages 43-61 In Proceedings of the International Pearl Millet Workshop, 7-11 Apr 2006, ICRISAT Center; 2006.
6. ICRISAT. Production Trends in pearl millet production: International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India; 2007.
7. Yadav OP, Rai KN, Khairwal IS, Rajpurohit BS, Mahala RS. Breeding pearl millet for arid zone of north western India: Constraints, Opportunities and approaches. All India Coordinated Pearl Millet Improvement Project, Jodhpur, India; 2011.
8. Yadav MS, Duhan JC. Effect of fungicidal seed treatment by seed dresser on storage life and survival of smut spores of pearl millet. Crop Research. 1999;18:124-126.
9. Singh SD. Sources of resistance to downy mildew and rust in pearl millet. Plant Disease. 1990;74:871-874.
10. Vadez V, Hash T, Bidinger FR, Kholova J. Phenotyping pearl millet for adaptation to drought. Frontiers of Physiology. 2012;3: 1-12.
11. Yadav OP. Pearl millet breeding: achievements and challenges. Plant Breeding Abstracts. 1996;66:157-163.
12. Yan W, Racjan I. Biplot analysis of test sites and trait relations of soybean in Ontario. Crop Science. 2002;42:11-20.
13. Cooper M, DeLacy IH. Relationships among analytical methods used to study genotypic variation and genotype-by-environment interaction in plant breeding multi-environment experiments. Theoretical and Applied Genetics. 1994; 88(5):561-572.
14. Gupta SC, Ndoye AT. Yield stability analysis of promising pearl millet genotypes in Senegal. Maydica. 1991;36: 83-86.
15. Haussmann BIG, Rattunde HFW, Weltzien-Rattunde E, Traoré PSC, vom Brocke K, Parzies HK. Breeding strategies for adaptation of pearl millet and sorghum to climate variability and change in West Africa. Journal of Agronomy and Crop Science. 2012;198:327-339.
16. Crossa J. Statistical analysis of multi-locational trials. Advances in Agronomy. 1990;44:55-85.
17. Yan W, Kang MS, Ma B, Woods S, Cornelius PL. (GGE Biplot vs. AMMI Analysis of genotype-by-environment data. Crop Science. 2007;47(2):245-252.
18. Khairwal IS, Rai KN, Diwakar D, Sharma YK, Rajpurohit BS, Nirwan B, Bhattacharjee R. Pearl millet: Crop management and seed production manual. International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India. 2007;104.
19. Kiprotich F, Kimurto PK, Ombui P, Towett B, Jeptanui L, Ojulong H, Lagat N. Multivariate analysis of nutritional diversity of selected macro and micro nutrients in pearl millet (*Pennisetum glaucum*) varieties. African Journal of Food Science. 2015;9:21-31.
20. Directorate of Plant Protection (DPP). Pearl millet production guide. DPP, South Africa; 2011.
21. ICRISAT. Annual reports. International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India; 2009.
22. IBPGR & ICRISAT. Descriptors for Pearl Millet (*Pennisetum glaucum* (L.). IBPGR & ICRISAT, Rome; 1993.
23. CIMMYT. Integrated breeding platform's breeding management system version 3.0 (IBP-BMS). Integrated Breeding Platform, CIMMYT, Veracruz, Mexico; 2014.
24. Payne RW, Murray DA, Harding SA, Baird DB, Souter DM. GenStat for windows 14th edition introduction. VSN International, Hemel Hempstead; 2012.
25. Yan W, Hint LA, Sheng Q, Szlavnics Z. Cultivar evaluation and Mega-environment investigation based on the GGE biplot. Crop Science. 2000;40:597-605.
26. Gebre W. Evaluation of pearl millet (*Pennisetum glaucum* L.) genotypes for yield and yield stability in South Omo and

West Hararghe. Journal of Biology, Agriculture and Healthcare. 2014;4(8):99-121.

27. Ezeaku IE, Angarawai II, Aladele SE, Mohammed SG. Genotype by environment interactions and phenotypic stability analysis for yield and yield components in parental lines of pearl millet (*Pennisetum glaucum* [L.] R. Br). African Journal of Agricultural Research. 2014;9(37):2827-2833.
28. Misra RC, Das S, Patnaik MC. AMMI analysis of stability and adaptability of late duration finger millet (*Eleusine coracana*) genotypes. World Journal of Agricultural Sciences. 2010;6(6):664-669.
29. Gupta SK, Rathore A, Yadav OP, Rai KN, Khairwal IS, Rajpurohit BS, Das RR. Identifying mega-environments and essential test locations for pearl millet cultivar selection in India. Crop Science. 2013;53(6):2444-2453. Available:https://doi.org/10.2135/cropsci2013.01.0053
30. Chin Ong, Monteith JL. Response of pearl millet to light and temperature. Field Crops Research. 1985;11(2-3):141-160.
31. Abdelrahman SH, Abdallah AH. Stability analysis in some upland Cotton (*Gossypium hirsutum* L) and pearl millet genotypes. University of Khartoum Journal of Agricultural Science. 2006;14(2):326-342.
32. Matus-Cadiz MA, Hucl P, Peron CE, Tyler RT. Genotype × environment interaction for grain colour in hard white spring wheat. Crop Science. 2003;43 :219-226.
33. Panwar LL, Joshi VN, Ali M. Genotype × Environment interaction in scented rice. Oryza. 2008;45:103 -108.
34. Yan W, Hunt LA. Biplot analysis of multi-environment trial data. In: Kang, M.S.(ed) Quantitative Genetics, Genomics and Plant breeding. CAB International. 2002;289-303.
35. Yan W, Kang MS. GGE biplot analysis: A graphical tool for breeders, geneticists, and agronomists. CRC Press, Boca Raton, FL; 2003.
36. Mashiri CE, Chikerema P, Murewi CTF, Gonzo L, Maposa S, Pfupajena MH, Sisito G. Estimating environmental effects using the agronomic traits of pearl millet varieties by means of the biplot technique. International Journal of Advanced Scientific and Technical Research. 2014; 2(4):72-91.
37. Mustapha M, Bakari HR. Statistical evaluation of genotype by environment interactions for grain yield in millet (*Pennisetum glaucum* (L.) R. Br). International Journal of Engineering and Science. 2014;3(9):7-16.

Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sciencedomain.org/review-history/23458