



Determination of yield stability of seven soybean (*Glycine max*) genotypes across diverse soil pH levels using GGE biplot analysis

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ABSTRACT

Objectives: The combined effects of genotype, environment and genotype x environment (GxE) interaction determine the yield of a crop. For the purpose of genotype evaluation, only genotype and GxE interactions are relevant to selection. This study was carried out to study adaptation and stability of soybean varieties over six soil pH regimes. Adaptability and stability are important breeding parameters under conditions of high rainfall and low soil pH.

Methodology and results: One improved and six local soybean genotypes were tested for two consecutive years (2004-2005) over a range of soil pH conditions of between 3.5 and 7.0. The experiments were conducted in a factorial design laid out in a completely randomized design with three replications. The genotypes were grown in the polythene bags at the research field of Department of Crop Science, University of Nigeria, Nsukka. The soil media were adjusted to the required pH levels using 1.0 N hydrochloric acid and calcium hydroxide. At harvest, data on some of the root and yield parameters were collected across all the soil pH conditions evaluated. The results showed high contributions of environment (E) to the total yield variation in the two planting seasons. ANOVA showed that genotype, soil pH and their interactions varied significantly ($p < 0.01$) in both years. The GGE biplot explained 94.3 and 93.3% of the genotype main effect and GE interaction in 2004 and 2005, respectively. The genotypes, *Kyado* and *TGX1448-2E* were the most superior for seed yield per plant in 2004 and 2005 plantings, respectively while cultivar *Gembu* performed poorly in both years. Genotype *Gembu* was consistently poor in yield performance, hence the high stability observed. In the 2004 planting, soil pH between 5.5 and 6.5 were representative but non discriminating among the test environments. However, in 2005 planting, soil pH 7.0 was the most discriminating and representative of the test environments; and therefore useful for culling genotypes that performed poorly. The stability analysis showed that none of the high performing genotypes was stable for seed yield.

Conclusion and application of findings: Cultivation of the genotypes, *Kyado* and *TGX1448-2E* is likely to improve soybean production in the regions with high precipitation usually associated with low soil pH. Thus, *Kyado* and *TGX1448-2E* were selected as superior for improved seed yield based on their mean performance. These genotypes could be used in a breeding program to develop genotypes with high yield potential. None of the high performing genotypes evaluated was stable across the soil pH environments, suggesting that each genotype has specific soil pH requirements. Cultivar, *TGX1448-2E* has neutral

response to varying soil pH; *Kyado* and *Sebore* performed well in soil pH 5.5 - 6.5, indicating that they are relatively tolerant to moderately acidic soil and therefore are good candidates for breeding acid tolerant soybean genotypes. This study shows that GGE biplot analysis is appropriate for identifying and discriminating genotypes across soil pH environments.

Key words: Derived Savannah agro-ecology, Genotype x environment interaction, GGE Biplot analysis, *Glycine max* and Multi-environment trials

INTRODUCTION

Soybean (*Glycine max* (L.) Merr) is one of the oldest legumes in the history of crop cultivation and belongs to the family *fabaceae*. Soybean occupies an important position among the grain legumes due to its economic importance (Dugje et al. 2009) and high protein supplements (Agwu et al. 2008). The United States of America is the leading producer of soybean where its oil is used in salad, milk, yoghurt and margarine manufacturing (Faryna, 1985). In Nigeria, soybean production is concentrated in the southern guinea savanna with an average annual rainfall of 1400 mm.

Interest in soybean production in Africa has increased considerably over the past few decades. This is attributable to a number of factors such as increased utilization of most commercially grown pulses as supplements in livestock feed (Uguru, 1996), usefulness as a source of cheap quality plant protein (Nnanyelugo et al., 1985) and the increasingly prohibitive cost of animal protein (Ene-Obong and Carnovale, 1992). To satisfy the demand by producers and consumers, a number of soybean varieties with excellent seed quality and agronomic characteristics have been released for cultivation by farmers in the tropical Africa (FAO, 1999) with the aim of increasing production and enhancing protein intake of the low and middle income earners. Farmers have shown increasing interest and soybean production has been

extended to the high rainfall belts of sub-Saharan Africa. Although there is considerable potential for soybean production in these belts (Mutsaers, 1991), yield has varied considerably in farmers' fields (Baten, 1991). This is attributable in part to continuous decline in soil fertility, due to deficiency in organic matter and other essential nutrients (Maduakor, 1991). The high rainfall is associated with leaching, low pH, erosion of mineralized and applied nutrients; the consequence of which is poor grain yield and reduced nodulating potentials of the native *Rhizobium* strains. Low pH is one of the most important biotic constraints affecting soybean production especially in the high rainfall belts. Zeigler et al. (1995) reported that acidic soils characterised by low pH and excess of aluminium and manganese, hamper crop production in tropical and sub tropical areas. Aluminium toxicity is considered a primary factor in limiting plant growth in acid soils (Foy 1988, 1992). The adaptability and stability of soybean genotypes over a wide range of soil pH environments in this region has not been investigated. Yet, soybean is continually being introduced for cultivation in the high rainfall ecologies with low soil pH, which may have some implications on yield since different genotypes respond differently to a specific environment. Therefore, this study was initiated to evaluate soybean genotypes for yield stability across different pH levels.

MATERIALS AND METHODS

Description of study site: Two experiments were conducted in the raining seasons of April to August in 2004 and 2005 planting seasons. The study site was located in the Research and Teaching Farm of the Department of Crop Science, Faculty of Agriculture, University of Nigeria, Nsukka (Lat. 06° 52'N; Long. 07 24' E; Alt. 447.2 m a.s.l.). The research field contains

the "B" soil type in University of Nigeria, Nsukka soil survey map. It is a well drained ferrallitic sandy loam soil of Nkpolpgu series. The monthly temperature, number of rainy days and rainfall distribution of the location during the crop growing periods are presented in **Table 1**.

Soybean seeds: Seeds of seven soybean genotypes

were used. These included one improved soybean genotype, *TCX1448-2E* obtained from the National Cereal Research Institute (NCRI), sub-station at Yadev, Benue State and six local soybean genotypes. The local soybean genotypes comprised *Digil*, *Garkida* and *Sebore* from Adamawa State, *Kyado* from Benue State and *Gembu* and *Sunkani* from Taraba State. Three genotype seeds were planted in each of the polythene bags but were letter thinned down to one after seed emergence. The data collected were based on the genetic expressions of the individual plant.

Soil samples were collected at random from different locations in the research field using a soil auger, from 0-20 cm depth in a 2-year fallow field, and bulked to form a composite sample. Four kilograms samples of the soils were weighed into each of 189 polythene bags and moistened to 60% Field Capacity (FC). The potted soils were adjusted to different pH levels using 1.0 N hydrochloric acid and calcium hydroxide. Ten grammes of the composite sample were sieved (2 mm), moistened to field capacity and were analyzed to ascertain the amount of HCl and Ca(OH)₂ required for the amendment to obtain the different pH levels.

The initial pH of the soil was taken at the beginning of the experiment (Table 2) and the pH of the potted soils was repeatedly determined at 2-weekly intervals for twelve weeks. Mechanical analysis of the soil was carried out by the Bouyous hydrometer method as described by Gee and Bauder (1986). Soil pH was measured using McLean (1982) method whereas organic carbon content was determined using weight combustion method as described by Nelson and

Sommers (1982). Cation Exchange Capacity (CEC) of the soil was determined by Ammonium Acetate method as described by Thomas (1982). Total nitrogen was determined using the micro kjedahl method as described by Bremmer and Mulvaney (1982) and available phosphorus was obtained according to Olsen and Sommers (1982). The experimental design was factorial laid out in a completely randomized design (CRD) with three replications. Data on seed yield per plant were collected from all the soil pH environments during the two planting seasons.

Statistical analysis: Combined analysis of variance (ANOVA) was used to determine the effects of genotype (G), environment (E) and genotype by environment (GE) interaction using the Genstat Discovery Edition 3 (Genstat 2007) software. The test of significance was done as described by Obi (2002). Genotype and genotype x environment (GGE) biplots were conducted using GGE biplot software (Yan *et al.*, 2000; Yan and Kang 2002) to determine seed yield stability and, to identify superior genotypes. GGE biplot analysis was also used to generate graphs showing (i) comparison of environments to ideal environment (Yan and Kang, 2003), (ii) "which-won-where" pattern and (iii) environment vectors. The angles between environment vectors were used to judge correlations (similarities/dissimilarities) between pairs of environments (Yan and Kang, 2003). The Pearson correlation coefficients were calculated to determine the exact correlation values of the environments using SPSS statistical software.

Table 1: Mean temperature (°C), rainfall (mm) and the number of rain days during the experimental period

Month	Temp (°C) (± SEM)**		Rainy days	Rainfall (mm) (± SEM)**
	Min.	Max.		
2004 planting				
January	21.032±0.421	32.58±0.23	1	0.049±0.049
February	22.448±0.328	34.38±0.26	0	-
March	23.516±0.282	34.00±0.44	3	1.188±0.222
April	22.80±0.251	31.90±0.32	6	1.896±1.250
May	23.55±0.331	29.897±0.332	20	8.30±2.436
June	21.761±0.254	28.875±0.232	13	9.37±3.32
July	20.839±0.132	27.645±0.256	18	5.374±1.802
August	20.839±0.132	27.645±0.256	23	5.440±1.459
September	20.467±0.202	28.133±0.224	21	11.311±2.725
October	20.839±0.208	29.23±0.28	14	4.810±1.274
November	21.667±0.316	30.00±0.22	5	2.625±1.599
December	19.742±0.562	31.94±0.23	1	0.0490±0.0490
2005 planting				

January	20.226±0.346	31.68±0.36	0	-
February	22.857±0.271	34.93±0.20	2	2.522±1.897
March	23.323±0.199	34.48±0.27	2	0.484±0.459
April	23.167±0.245	33.63±0.40	10	4.936±2.651
May	22.258±0.250	30.68±0.35	11	4.597±1.519
June	21.833±0.292	29.47±0.30	18	10.79±3.30
July	20.968±0.276	28.32±0.33	20	8.267±2.602
August	20.387±0.195	27.387±0.306	17	4.048±1.765
September	21.500±0.239	28.73±0.20	19	6.935±2.307
October	21.161±0.241	30.10±0.23	16	17.71±9.87
November	21.367±0.490	32.43±0.19	1	0.3387±0.3387
December	20.710±0.298	32.42±0.21	1	0.0410±0.0410

Table 2: Amount of lime and Hydrochloric acid that were added to the soil samples at the beginning of the experiments

pH	Amount of lime (Ca(OH) ₂) or Hydrochloric acid (HCl) added per 4kg to amend soil pH
7.0	4.4 g Ca(OH) ₂
6.5	3.2 g Ca(OH) ₂
6.0	2.3 g Ca(OH) ₂
5.5	1.2 g Ca(OH) ₂
5.0	No amendment
4.5	12 cm ³ Hcl
4.0	36 cm ³ Hcl
3.5	64 cm ³ Hcl

RESULTS

The mean squares of the genotypes, environments and genotype x environment (G x E) interaction were highly significant ($P < 0.01$) in both 2004 and 2005 plantings (**Table 3**). In 2004, about 56 % of the total variation was due to the genotype effect, while the environment and genotype x environment interactions accounted for 37.36 and 6.31 %, respectively. In 2005, the genotype, environment and genotype x environment interactions accounted for 38.16, 54.06 and 7.76 % of the total variation, respectively.

Results (table 4) showed that in 2004 the genotype *Kyado* produced the highest seed yield per plant (4.292 g), followed by *Sebore* (3.572 g) and *TGX1448-2E* (2.583 g) while *Gembu* produced the lowest seed yield per plant (0.892 g). With respect to the soil pH environments, genotypes recorded significantly higher mean seed weight under soil pH of 6.5 (3.216 g), followed by soil pH of 6.0, 5.5 and 7.0 with mean seed weight of 2.999 g, 2.640 g and 2.804 g, respectively. The lowest seed weight per plant (0.960 g) was obtained at soil pH of 4.5. The genotype x environment

interaction showed that seed weight per plant varied from 0.54 to 6.53 g.

In the 2005 planting season, *TGX1448-2E* produced significantly ($P < 0.01$) higher mean seed yield per plant (3.898 g) than the local varieties. It was closely followed by *Garkida* (2.473 g), *Kyado* (2.447 g), *Sunkani* (2.067 g) and *Digil* (2.040 g). Similar to the result obtained in 2004, *Gembu* recorded the lowest seed weight per plant (0.885 g). Soil pH of 6.5 supported the best performing lines in terms of the seed yield per plant (**Table 4**). This was followed by the seed yield in the soil of pH 6.0 (2.353 g) and 7.0 (3.321 g) while soil of pH 4.5 recorded the lowest (1.017 g) seed weight per plant. The genotype x environment interaction analysis showed that seed weight per plant varied from 0.41 to 7.36 g

Table 3: Analysis of variance of the effects of genotypes, environments and their interactions on soybean seed yield per plant.

Source of variation	DF	MS		% Variation	
		2003	2004	2003	2004
Genotype	6	26.4097**	14.8410**	56.24	38.16
soil pH (Environment)	5	17.5439**	21.0268**	37.36	54.06
Genotype x soil pH	30	2.9639**	3.0166**	6.31	7.76
Error	82	0.0399	0.0078	0.00085	0.0002

* and ** = Significant at 5% and 1%, respectively

Table 4: Seed yield performance (g) of seven soybean genotypes evaluated under six soil pH environments during the 2004 and 2005 planting seasons.

Genotype	Soil pH (Environment)							Soil pH (Environment)						
	4.5	5.0	5.5	6.0	6.5	7.0	Mean	4.5	5.0	5.5	6.0	6.5	7.0	Mean
	2004 planting season							2005 planting season						
<i>Digil</i>	0.74	1.51	1.25	1.84	1.75	1.77	1.477	0.65	1.23	1.59	2.66	3.55	2.56	2.040
<i>Garkida</i>	0.54	1.64	1.17	1.82	3.60	2.46	1.872	0.96	1.35	1.71	3.23	3.84	3.76	2.475
<i>Gembu</i>	0.67	0.74	0.81	0.94	0.83	1.36	0.892	0.41	0.66	0.96	0.90	0.4	1.54	0.885
<i>Kyado</i>	1.34	2.73	6.53	6.32	4.71	4.12	4.292	1.96	2.96	2.02	1.33	2.73	3.68	2.447
<i>Sebore</i>	1.85	1.38	5.03	5.30	4.69	3.18	3.572	0.76	0.97	2.49	2.18	2.15	2.25	1.800
<i>Sunkani</i>	0.83	0.96	1.49	2.30	3.31	1.57	1.743	0.80	1.12	1.38	3.27	3.73	2.10	2.067
<i>TGX1448-2E</i>	0.75	1.29	2.20	2.47	3.62	5.17	2.583	1.58	1.67	2.53	2.90	7.35	7.36	3.898
Mean	0.960	1.464	2.640	2.999	3.216	2.804		1.017	1.423	1.811	2.353	3.456	3.321	

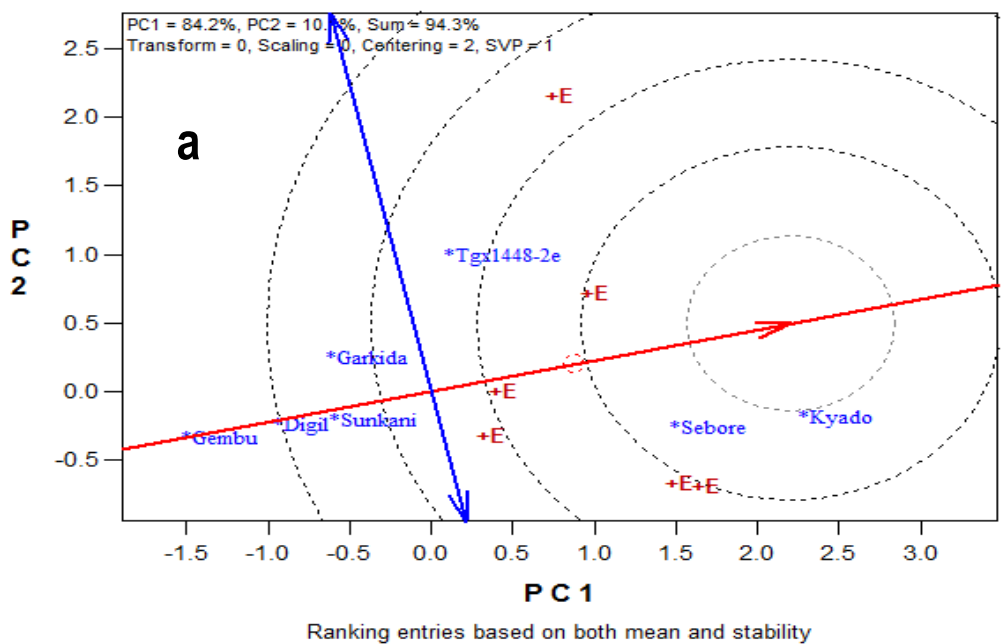
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for:

Genotype (G)	0.132	0.059
soil pH (E)	0.123	0.054
G x E	0.324	0.144

The GGE biplot presents the main genotype effect (G) and the genotype x environment interaction (GE) of multi-environment tests. The GGE biplot analysis permits comparison among genotypes with a reference genotype. This method specifies the position of an "ideal" genotype, which will have the highest average value of all genotypes and be absolutely stable; that is, it expresses no genotype by environment interaction. A set of concentric circles are created using the ideal genotype at the concentric center. The ideal genotype is used as a reference to rank the other genotypes. A performance line passing through the origin of the biplot is used to determine mean performance of a genotype. The arrow on the performance line represents increasing mean performance. A stability line perpendicular to the performance line also passes through the origin of the biplot; the two arrows in opposite directions represent decreased stability. A genotype further from the biplot origin on either side of the stability line represents relatively lower stability.

The results of the GGE biplot for the 2004 and 2005 planting seasons are presented in Fig. 1. Fig. 1 (a) shows that the GGE biplot explained 94.3% of the genotype main effect and the GE interaction. The primary (PC1) and secondary (PC 2) scores explained 84.2 and 10.1% of the genotype main effect and the GE interaction, respectively. The genotype, *Kyado* was closest to the point of the ideal genotype followed by *Sebore* while *Gembu* was farthest from the point of the ideal genotype (concentric circle) during the 2004 planting season. In 2005 planting season (Fig. 1 (b)), the first two PCs explained 93.3% (PC1=79.7%, PC2=13.5%) of the total GGE variation. The results indicated that *TGX1448-2E* was the most superior for seed yield by being the closest to the point of the ideal genotype, followed by *Kyado* and *Garikida* in that order. However, *Gembu* ranked last for seed yield per plant among all genotypes by being farthest from the point of the ideal genotype (Fig. 1(b)).



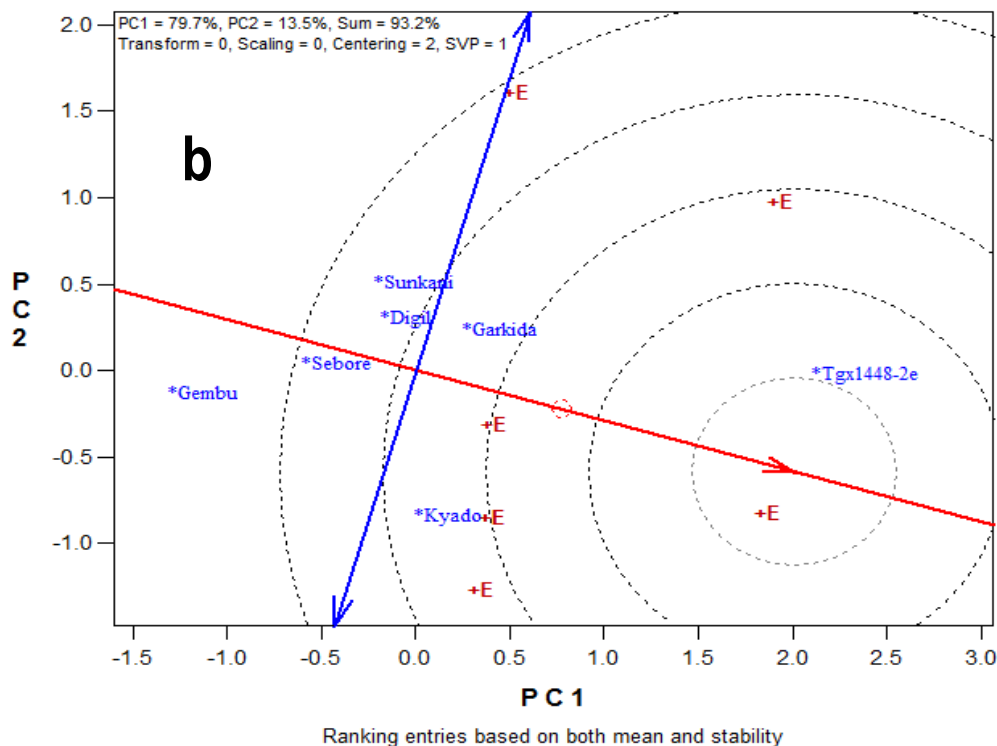


Figure 1: GGE-biplot based on genotype-focused scaling for comparison among the genotypes with the ideal genotype.

Results on yield performance and stability of the seven soybean genotypes across the soil pH environments in 2004 and 2005 planting seasons are shown in Fig 2 (a) and (b). The AEA (the single-arrwed line) points to higher average seed weight while the double-arrwed line, the AEC coordinate, points to greater variability (smaller stability) in either direction. In the 2004 planting, *Kyado* recorded the highest average seed yield per plant, followed by *Sebore* and *TGX1448-2E* while *Gembu* had the lowest seed yield. The results

also indicated that the genotypes *TGX1448-2E*, *Kyado* and *Sebore* had the longest AEC [Fig. 2 (a)]. In 2005 [Fig. 2 (b)], *TGX1448-2E* was the highest yielding genotype but was also found to have high AEC value. The mean seed weight of *Kyado* and *Garikda* were relatively similar to the grand mean with the former and latter having long and short AEC value, respectively. *Gembu* was again the least performing genotype in 2005.

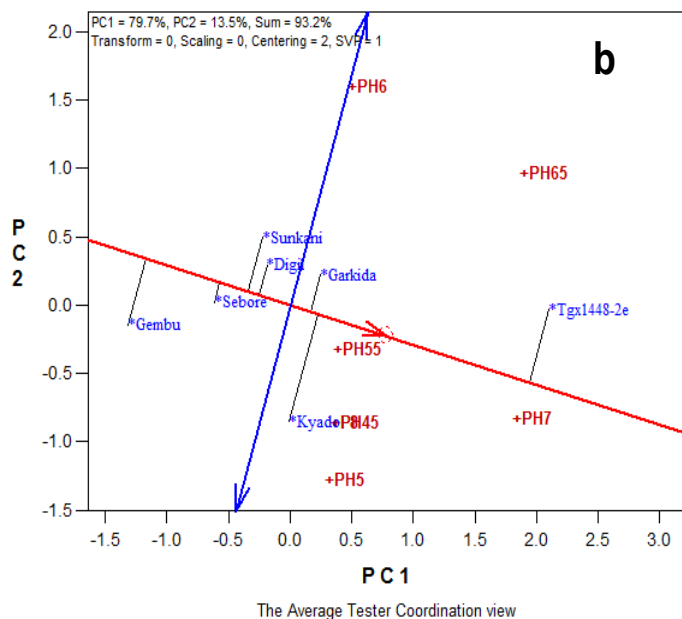
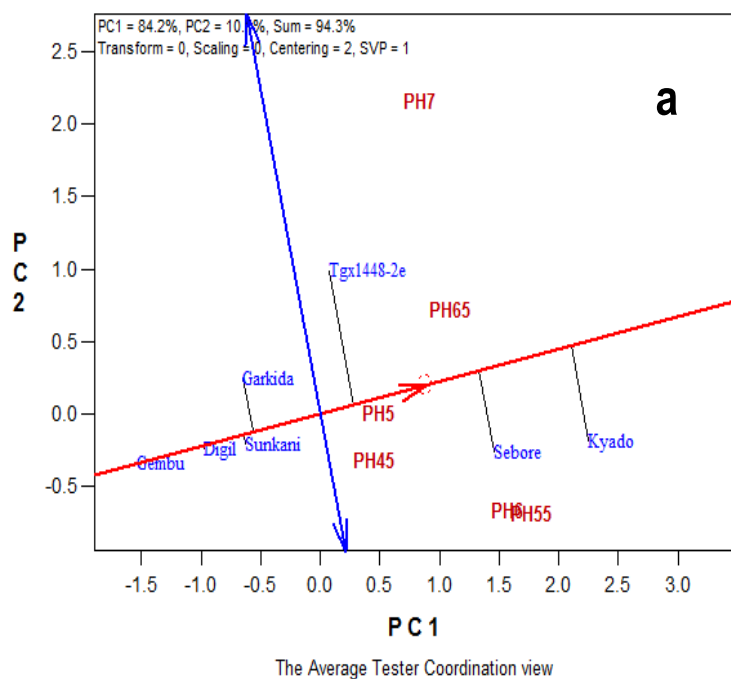


Figure 2: Yield stability and performance of seven soybean genotypes in 2004 (a) and 2005 (b) planting seasons.

The polygon views of the seed yield per plant in 2004 and 2005 planting seasons are shown in Fig. 4(a) and (b). The winning genotypes for each environment are located on the vertex of the polygon. In 2004 [Fig. 3 (a)], *TGX1448-2E* was the vertex genotype at soil pH of 7.0 while *Kyado* was the winner genotype in the environment with soil pH 5.5, 6.0 and 6.5; followed by cultivar *Sebore*. However, the genotype, *Gembu* was

the poorest in all the soil pH environments evaluated. Results of the 2005 planting season [Fig. 3 (b)] showed that *TGX1448-2E* was the winning genotype at soil pH environments of 6.5 and 7.0. The genotype *Sebore* showed average performance in all soil pH environments while *Sunkani* and *Gembu* performed poorly in all the soil pH environments evaluated (Fig. 3 (b)).

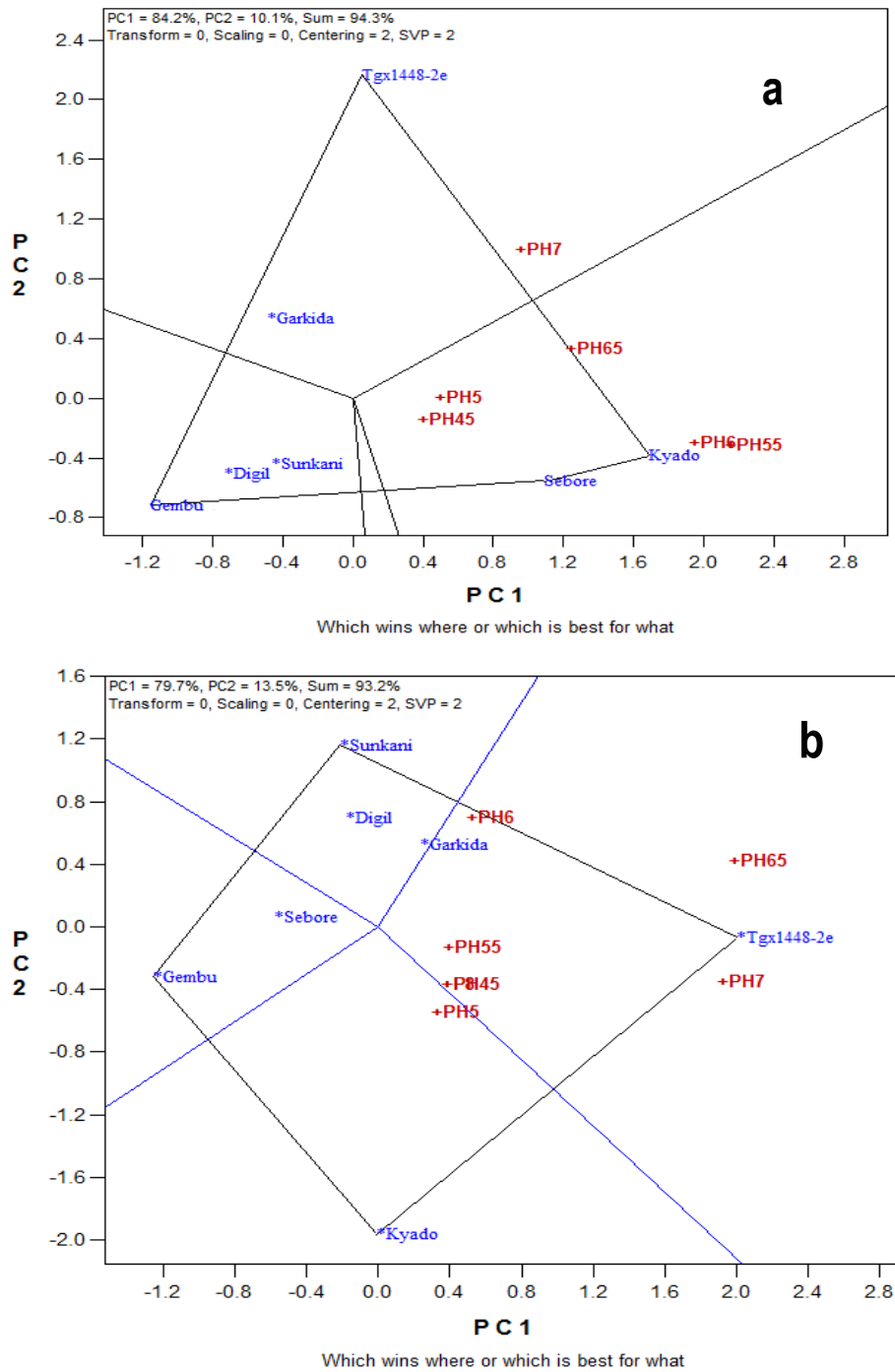


Figure 3: Biplot of winning genotype of seven soybean genotypes in seven soil pH levels using the “which wins where or which is best for what” approach.

The comparison of soil pH environments with the ideal soil pH environment is presented in **Fig. 4 (a)** and **(b)**.

The 2004 planting season [Fig. 4 (a)] indicated that soil pH of 5.5, 6.0 and 6.5, which were nearer to the center of concentric circles, were the favourable soil pH environments for increased soybean seed yield while soil pH values of 4.5, 5.0 and 7.0 were unfavourable. The 2005 planting [(Fig. 4 (b))] indicated that soil pH 7.0 which is at the center of the concentric circles, was the ideal test environment in terms of being the most

representative of the overall soil pH environments and the most powerful to discriminate the genotypes. The result also showed that the soil pH environment of 6.5 was favourable. On the other hand, the unfavourable soil pH environments were pH 4.5, 5.0, 5.5 and 6.0. The favorable and ideal environments showed high yield potential and the unfavorable ones had low yield potential (Table 3).

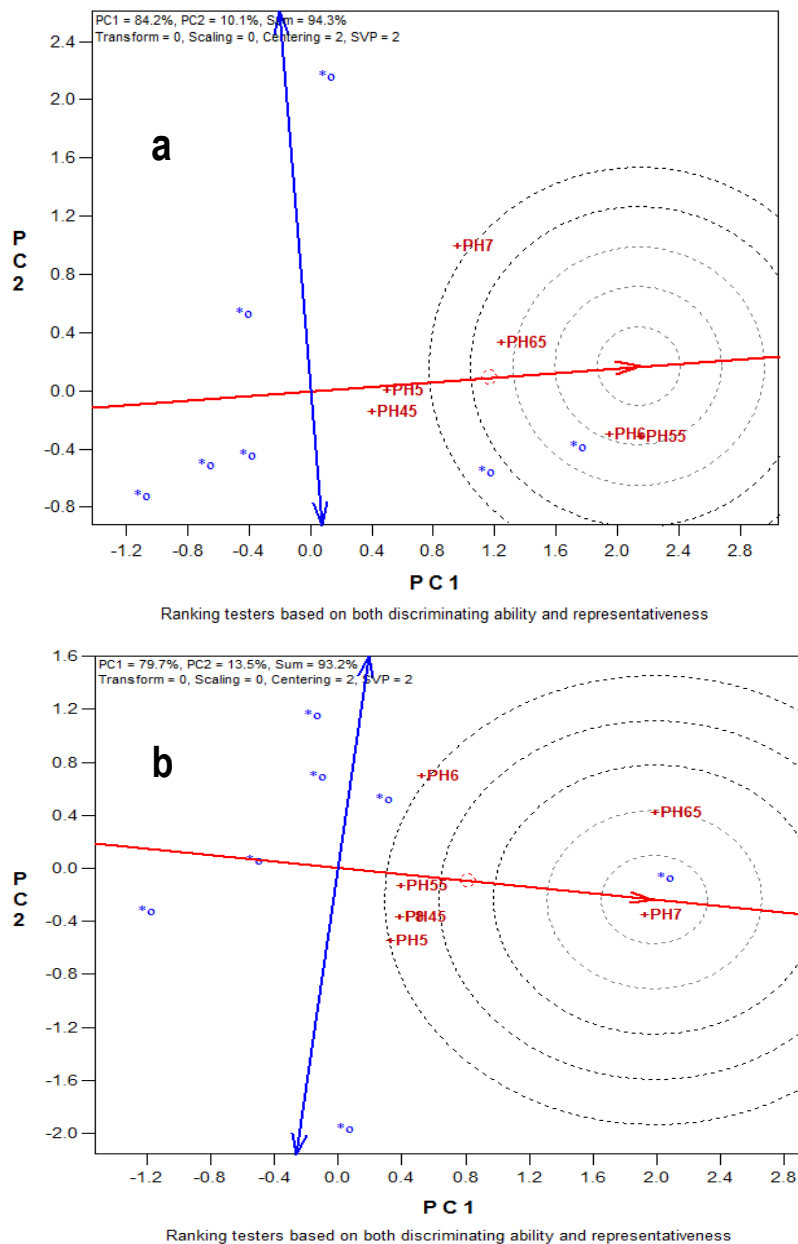


Figure 4: The discrimination and representativeness view of the GGE biplot to rank test environments relative to an ideal test environment (represented by center of the concentric circles)

The correlation coefficients among the test soil pH environments are presented in **Table 5**. The vector view of the GGE-biplot which provide a succinct summary of the interrelationships among the environments during the 2004 and 2005 planting seasons are presented in **Fig. 5 (a)** and **(b)**. The test environments assessed on the basis of seed yield per plant showed wide diversity among the soil pH environments. All the environments had the same PC1 score sign in both 2004 and 2005 planting seasons. The cosine of the angle between the vectors of 2 environments is related to the correlation coefficient between them. Two environments are positively correlated if the angle between their vectors is $<90^\circ$, negatively correlated if the angle is $>90^\circ$, independent if the angle is 90° . The environments with longer vectors are more discriminative of the genotypes, and short vectors are less discriminative. **Fig. 5 (a)** showed acute

angle relationships among all the the test environments, with the angle between the soil pH 5.5 and 6.0 being the smallest. Results (Table 4) revealed that the two soil pH environments had the highest positive and highly significant correlation value of 0.992**. The environment at pH 4.5 correlated significantly positively with soil of pH 5.5 ($r = 0.85^*$) and pH 6.0 ($r = 0.867^*$), while soil pH of 6.5 correlated positively well with soil of pH 5.5 ($r = 0.769^*$) and 6.0 ($r = 0.818^*$). However, soil of pH environment 7.0 had a non significant correlation with all the test environments in the 2004 planting seasons (**Table 5**). The 2005 planting season [**Fig. 5 (b)**] also revealed an acute angle relationships among all the soil pH environments. The soil pH of 7.0 had a positive and significant correlation with soil pH of 6.5 ($r = 0.897^{**}$) while the soil pH of 4.5 was significantly and positively correlated with soil pH of 5.5 ($r = 0.934^{**}$) (**Table 5**).

Table 5: Correlation coefficients among test environments in 2004 and 2005 planting seasons

Environments (soil pH)	pH 4.5	pH 5.0	pH 5.5	pH 6.0	pH 6.5	pH 7.0
2004 Planting Season						
4.5	1					
5.0	.354	1				
5.5	.850*	.747	1			
6.0	.867*	.740	.992**	1		
6.5	.651	.609	.769*	.818*	1	
7.0	.322	.507	.574	.548	.660	1
2005 Planting Season						
4.5	1					
5.0	.934**	1				
5.5	.590	.396	1			
6.0	-.030	-.156	.232	1		
6.5	.496	.255	.546	.667	1	
7.0	.692	.442	.653	.334	.897**	1

** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).

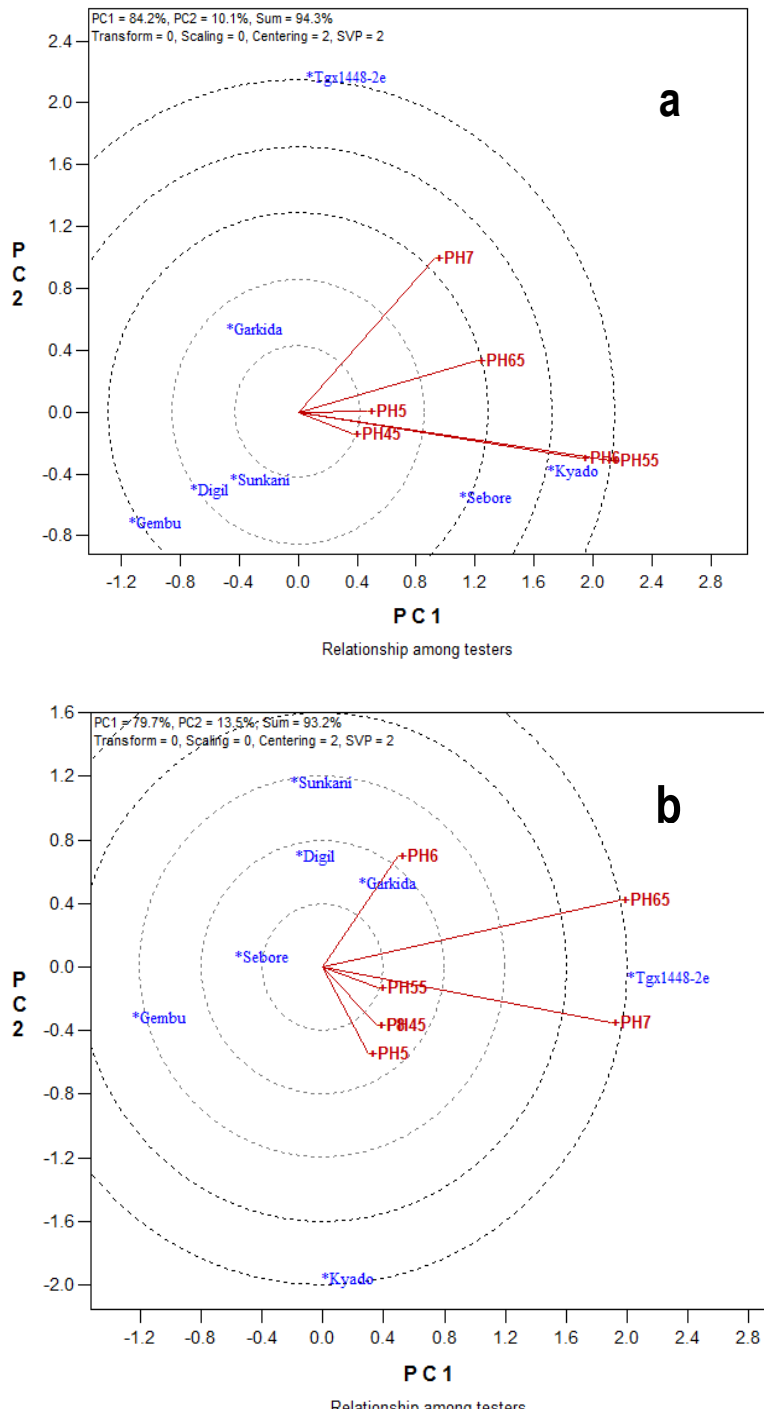


Figure 5: Relationships among genotypes, test pH environments and genotype x testing environment interaction for (a) 2004; (b) 2005 planting season.

DISCUSSION

The highly significant differences among the genotypes in both 2004 and 2005 planting seasons suggest the presence of genetic variability among the genotypes with respect to seed yield per plant and, this could be exploited in selection for acidity tolerance. Akparobi (2009), Alghamdi (2009) and Gurmu *et al.* (2009) have reported the existence of genetic variations among some soybean genotypes. The genotypes, *Kyado* and *TGX1448-2E* recorded the highest seed yield per plant in the 2004 planting (4.292 g) and 2005 planting (3.898 g), respectively. *Kyado* and *TGX1448-2E* are therefore promising genotypes for high rainfall zones characterized by low soil pH. Notwithstanding that the soil pH conditions were same at both 2004 and 2005 planting seasons, the genotypes behaved differently due to the variations observed in the weather conditions during the plant's growing seasons.

The genotypes responded differently across all the soil pH environments in both 2004 and 2005 planting seasons, which is an indication that the soil pH environments evaluated had discernable influence on the genotypes yield performance. This is validated by the relatively high contributions of the soil pH environments to the percentage variation observed, especially in the 2004 planting season. Kaya *et al.* (2002; 2006) reported that a large sum of squares for environments indicates the presence of variation in the test environments, with large differences among environmental means causing most of the variation in the crop yield. Therefore, the significance of the test environment on the seed yield showed strong influence of soil pH on the performance of soybean genotypes. These results revealed the need to identify the ideal soil pH environment and genotype that showed wide adaptation across the test environments. This would be beneficial to breeders, in developing stable and high yielding soybean genotypes.

The genotypes produced the highest seed yield per plant in soil of pH 6.5 in both planting seasons. Beyond this pH level, seed yield increase was not significant. This is an indication that soil pH of 6.5 is optimal for growing soybean. Soybeans grow best in slightly acidic soil but can tolerate a range of soil pH between 5.8 and 6.5 (Franzen, 1999; Hans, 2010). Genotypes showed poor performance in soil pH environments between 4.5 and 5.0 indicating that they are sensitive to acidic soil conditions. The result agrees with the report of Reddy and Dunn (1987) that high levels of soil acidity (low soil pH) can reduce root growth and reduce nutrient availability and hence, affect soybean growth and yield.

Zeigler *et al.* (1995) reported that acidic soils characterised by low pH and excess of aluminium and manganese hamper crop production in tropical and sub tropical areas. Earlier workers have shown that low pH inhibits the growth, development and yield of crop (Taylor, 1988; Mossor-Pietraszewska, 2003). They reported that the major limiting factor to plant productivity in most acid soils is aluminum (Al) toxicity and that plant roots are more sensitive to aluminium toxicity than the shoot. Studies have also shown that at low soil pH, phosphorus and some essential micronutrients are found to be less available to plants (Kamprath, 1984; Foy, 1992; Kochian *et al.*, 2004; Akinrinde *et al.*, 2005).

The ANOVA revealed that genotype x soil pH interactions were significant ($p < 0.05$) in both planting seasons suggesting that the interaction of genotypes with the soil environments is of considerable importance in determining relative seed yield in the soybean genotypes and, that there were substantial differences in genotypic response of the genotypes across all the soil pH environments evaluated. Considerable differences in response to soil pH are known to exist among genotypes like wheat (Soon, 1992), tomato, rice (Bowen, 1987), and common bean (Hacisalihoglu *et al.*, 2004). Previous studies on soybean have also shown strong genotype x soil pH interactions (Reddy and Dunn, 1987). Alghamdi (2009) reported that significant G x E interactions suggest that some genotypes were more stable than others across environments.

The significant effect observed in the Genotype x Environment interaction in both planting seasons is an indication of the possible existence of different mega-environments and that the genotypes ranked differently across diverse soil pH environments. Mega-environments is defined as a group of locations that consistently share the same best cultivar(s) (Yan and Rajcan, 2002). The large yield variation due to environment, which is irrelevant to genotype evaluation and mega-environment investigation (Ghaffari and Depao, 2005), suggests the use of GGE biplots as the appropriate tool for analyzing the multiple environment trials data (Samonte *et al.* 2005). The GGE concept is based on the understanding that genotypes main effect (G) and genotype by environment interaction (GEI) are the two sources of variation that are relevant to genotype evaluation and that they must be considered simultaneously, for appropriate genotype evaluation (Yan, 2005). Results of this study indicate that GE

interactions are more likely to occur for some genotypes. Moreover, the GGE biplot explained 94.3 and 93.2 % of the total percentage of the total yield variation observed during the 2004 and 2005 planting seasons, respectively. The high percentage variation observed would therefore justify the use of GGE biplot to identify discriminating genotype performance. GGE biplot analysis has recently been widely used to determine performance stability in multi-locational trials in order to identify superior genotypes (Sharma and Duveiller, 2007; Yan et al., 2007; Roozeboom et al., 2008).

This study identified superior genotypes with arrays of variability for seed yield stability. Even among the superior genotypes, a few could be considered more valuable based on the GGE biplot analysis, because they were closer than others to the point of the ideal genotype. These include *Kyado* followed by *Sebore* in 2004 and *TGX1448-2E* in 2005. These genotypes were positioned within or at the innermost circle of the biplots, which qualified them as outstanding among the genotypes. Superior genotypes are located closer to an ideal genotypes (Sharma et al., 2009). In this study, ideal genotype was not identified. An ideal genotype is defined as one that is the highest yielding across test environments (*i.e.*, one that ranks the highest in all test environments) (Yan and Kang, 2003). Such an ideal genotype is defined by having the greatest vector length of the high yielding genotypes and with zero GEI.

Notwithstanding that the genotypes *Kyado*, *Sebore* and *TGX1448-2E* recorded the highest seed weight per plant in the 2004 planting season, they were found to be unstable with *TGX1448-2E* being the most unstable genotypes by having the longest AEC. *Kyado* and *Sebore* out-yielded the hybrid genotype *TGX1448-2E* suggesting that they could be valuable candidates for the crop's improvement programme. In the 2005 planting season, the genotype *TGX1448-2E* was the highest yielding but was found to be unstable by possessing the longest AEC. However, *Kyado* and *Garikda* were relatively stable with the mean seed weight per plant that are very close to the grand mean. The genotype, *Gembu* performed consistently lowest in both 2004 and 2005 planting seasons. *Gembu* is therefore a poor yielding genotype under the derived savannah region and therefore should not be promoted for cultivation by farmers in the region. Also, more emphasis should be placed on the genotypes *Kyado*, *Sebore*, *Garikda* and *TGX1448-2E* during the improvement of the crop, having performed relatively

well in 2004 and 2005 planting seasons. The ideal goal for any crop improvement program is to generate genotypes that are environmentally buffered (stable) and high yielding (Zewdie and Poulos, 1995).

The "which-won-where" pattern indicated that four sectors were identified on the GGE biplot in both 2004 and 2005 planting seasons. Only two of the four sectors contained the soil pH environments and these were identified as the two mega-environments. In 2004 planting season, results indicate that *TGX1448-2E* was the highest-yielding genotype in soil of pH 7.0 while *Kyado* was the best yielding genotype in soil of pH 5.5, 6.0 and 6.5 followed by *Sebore*. The 2005 planting season showed that genotype *TGX1448-2E* was the highest-yielding genotype in soil of pH 6.5 and 7.0. The results indicate that *TGX1448-2E* performed best in soil of pH 7.0 in both 2004 and 2005 plantings which suggest that *TGX1448-2E* grows well at neutral soil pH and hence, very sensitive to both the alkaline and acidic soil conditions.

The "which-won-where" pattern revealed that none of the genotypes performed well at soil pH below 5.5 suggesting that these genotypes are better adapted to slightly acidic to neutral soil pH environmental conditions. However, *Kyado* and *Sebore* gave higher seed weight per plant at soil pH 5.5 during the 2004 planting, which could suggest that they are more tolerant to moderate soil acid conditions than the other genotypes. These genotypes may possess traits for soil acidity tolerance, and could be exploited in the improvement and breeding for acid tolerance. The "which-won-where" pattern facilitates the identification of superior genotypes and test environments that permit detection of such genotypes; a necessary condition for specific adaptation (Baker, 1988; Yan and Rajcan, 2002). Therefore, selection of superior genotypes for each environment ensures the effective exploitation of both G and GE interaction. Breeding for specific adaptation offers a sustainable solution on how to improve agricultural production in marginal areas. An interesting feature of this view of a GGE biplot is that the vertex genotype(s) for each sector has (have) higher (some times the highest) yield than the others in all environments that fall in the sector (Yan, 2002).

The soil pH environments of 6.0 and 6.5 were found to be nearer to the center of concentric circles during the 2004 planting season indicating that they are favourable test environments in terms of being the most discriminative and moderately representative. However, the soil pH environments of 4.5, 5.0 and 7.0 were less discriminative and representative and therefore were

considered to be unfavourable for growing the soybean genotypes evaluated. The 2005 planting season showed that soil pH of 7.0 fell into the center of concentric circles and, is therefore considered an ideal soil pH environment for the soybean genotypes. This environment was found to be the most representative of the overall soil pH environments and the most powerful to discriminate the genotypes. The soil pH environment of 6.5 was most representative and moderately discriminative which qualified it as a favourable environment. On the other hand, the pH of 4.5, 5.0, 5.5 and 6.0 were less favourable because they failed to discriminate among genotypes. The favorable and ideal environments showed high yield potential and the unfavorable ones had low yield potential. The ideal test environment should have large PC1 scores (more power to discriminate genotypes in terms of the genotypic main effect) and small (absolute) PC2 scores (more representative of the overall environments) (Yan et al., 2000; Yan and Rajcan, 2002). Such an ideal environment is represented by an arrow pointing to it. Although such an ideal environment may not exist in reality, it can be used as a reference for genotype selection in the multi-environmental yield trials (MEYTs).

An environment is more desirable if it is located closer to the ideal environment. Thus, using the ideal environment as the center, concentric circles were drawn to help visualize the distance between each environment and the ideal environment (Yan et al., 2000; Yan and Rajcan, 2002). The ideal test environment is therefore a point on the AEA in the positive direction ("most representative") with a distance to the biplot origin equal to the longest vector of all environments ("most informative"). Identification of an ideal test environment based on discriminating ability and representativeness implies that selections

CONCLUSIONS

Stability analysis is an important and efficient tool for plant breeders and agronomists. It helps to identify and select the most stable, high performing genotypes that are best suitable under a given set of environmental conditions. In the present study, prediction of mean yield performance across genotypes as well as varying soil pH conditions established the practical utility of studies on parameters of stability which will help to develop the breeding strategies for high productivity in

made at that site would have the highest probability of choosing superior genotypes that perform well in all environments in the growing region. Thus, major benefits to breeders would include the increased efficiency of selecting in discriminating environments and the discontinued use of poorly discriminating environments. In this way, cultivar development can be achieved most efficiently taking into account the limited resources available to plant breeders. The unfavourable soil pH test environments identified should be dropped from the testing program.

The vector view of the GGE-biplot and correlation results showed that the relationship of the soil pH 5.5 with 6.0, soil pH 4.5 with soil pH 5.5 and 6.0, soil pH 6.5 with soil pH 5.5 and 6.0 were positive and significant during the 2004 planting season. Such positive significant correlations among the test environments (soil pH) suggest that indirect selection for seed weight can be practical across the test environments. For instance, the genotypes adaptable or higher yielding in soil pH 5.5 may also show similar responses to soil of pH 6.0 as well. The non significant correlation observed between the soil pH 7.0 and the other soil pH values evaluated in the 2004 planting is an indication that soil pH 7.0 was distinct. This means that the soil pH value of 7.0 is different from the remaining pH values in term of supporting seed yield in the crop. During the 2005 planting season, highly significant positive correlation was obtained between soil pH of 7.0 and 6.5 indicating that the two test environments are similar with respect to supporting high yield in soybean genotypes. Although, soil pH of 4.5 and 5.5 showed significant positive correlation value, they were less discriminating among the genotypes and, therefore not suitable for selection of soybean genotypes based on their seed yield per plant.

areas prone to high soil acidity. Thus, from the findings of this study, it can be concluded that genotypes *Kyado*, *Sebore*, *Garikda* and *TGX1448-2E* had the high mean yield of seed yield per plant across the soil pH environments tested. These genotypes are suitable for cultivation in high rainfall areas and could be exploited in future breeding programs to develop high yielding, stable genotypes for acidic soil growing conditions.

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