International Journal of Agricultural Technology 2024 Vol. 20(1):315-328
Available online http://www.ijat-aatsea.com
ISSN 2630-0192 (Online)

GGE biplot analysis of genotype by environment interaction and yield stability of yardlong bean lines under nine environments

Pornsuriya, P.[1*], Chittawanij, A.[1], Yemor, T. [1], Chinaworn, S.[1] and Tira-umphon, A.[2]

[1]Department of Plant Production Technology, Faculty of Agriculture and Natural Resources, Rajamangala University of Technology Tawan-ok, Chonburi, 20110, Thailand; [2]School of Crop Production Technology, Institute of Agricultural Technology, Suranaree University of Technology, Nakhon Ratchasima, 30000, Thailand.

Pornsuriya, P., Chittawanij, A., Yemor, T., Chinaworn, S. and Tira-umphon, A. (2024). GGE biplot analysis of genotype by environment interaction and yield stability of yardlong bean lines under nine environments. International Journal of Agricultural Technology 20(1):315-328.

Abstract The results indicated significant environment (E), genotype (G), and genotype x environment (GE) effects for yield. The environmental main effect explained 77.68% of the total variation, whereas the genotype and GE explained 4.30% and 8.58%, respectively. The genotype plus genotype by environment (GGE) biplot of the first two principal components explained (PC1 = 69.99%) and (PC2 = 14.02%) of the GEI sum of squares. Bangpra2 (G2) was the most stable line since it was the highest total genotype GE score and the position closest to the ideal genotype from the GGE Biplot. NO.25 (G8) and No.30 (G9) were the second and third stable lines according to their GE scores and GGE biblot. The best environment for yield selection of the 10 genotypes was planted in Chonburi in the early rainy season and applied with chemical fertilizers (E3) since it had the highest total environment GE score and its position closest to the ideal environment from the GGE Biplot.

Keywords: Asparagus bean, GE scores, Ideal genotype, Ideal environment

Introduction

Yardlong bean (*Vigna unguiculata* subsp. *sesquipedalis* (L.) Verdc.) is one of the economically crucial vegetable crops of Thailand. It can be grown in all seasons and all regions of Thailand. According to The Department of Agricultural Extension (2022), the yardlong bean had around 6,437.5 hectares of plantation throughout the country, and it produced about 61,104 tons of crop during the 2021 planting season. In addition to growing yardlong beans for consumption and selling as fresh pods domestically, Thailand also produces yardlong bean seeds for export to other countries. In 2022, Thailand exported 114.26 tons of yardlong bean seeds, valued at 274.24 million baht (Office of Agricultural Economics, 2023).

* **Corresponding Author:** Pornsuriya, P.; **Email:** pornsuriya@hotmail.com

The yield stability of a plant variety is a significant and desired characteristic in crop breeding. Highly stable varieties are those that produce a constant average yield in all environmental conditions or have little variation in yield. Good varieties should have stable yields or not change the sequence of yields when environmental conditions change (Puddhanon, 2005). To enable a breeder to select high-yielding and reliable cultivars, the yield and stability performance of cultivars under various circumstances are necessary. Varieties that should be introduced to farmers for cultivation in various areas that have different environments must be tested in many environments, or sometimes there may be testing in one area. Still, the experiment can be modified to different environments, such as using planting dates, seasons, planting space, or different fertilizer rates (Ottai *et al.,* 2006).

Genotype-by-environment interaction (GEI) is a significant issue in crop breeding for two primary reasons: first, it slows down selection progress, and second, it makes crop suggestion challenging because it is unable to assess the primary effects statistically (Nwangburuka *et al.,* 2011). In breeding programs, GEI is crucial for selecting stable cultivars that are generally or precisely suitable for various environmental conditions (Verma *et al.,* 2008).

GEI can be assessed in both single-variate and multiple-variate analyses. The most commonly used single-variate analysis includes the Finlay and Wilkinson (1963) model and the Eberhart and Russell (1966) model. These two models do not take into account most of the GEI effects because they are regression analysis methods, which are univariate, while the GEI effects are multivariate (Akpan and Udoh, 2017). Therefore, the preferred technique for analyzing plant yield stability should be a multivariate analysis such as AMMI (additive main effects and multiplicative interaction) and GGE (genotype main effect and genotype-environment interaction) biplot analyses (Badu-Apraku *et al.,* 2012). Regarding mega-environment analysis and cultivar assessment, the GGE biplot is more effective than the AMMI1 chart since it describes more G+GE and possesses the inner-product property of the biplot (Yan *et al.,* 2007).

The GGE biplot method has been used to evaluate GEI and yield stability in several bean crops, including yardlong bean (Hossain *et al.,* 2018), common bean (Zanella *et al.,* 2019, Souza *et al.,* 2023), cowpea (Haisirikul *et al.,* 2020) and winged bean (Akinyosoye *et al.,* 2023). However, there is little information and research on applying the GGE biplot method to examine the GEI and yield stability of yardlong bean genotypes in Thailand. Therefore, the objectives were to evaluate the GEI and yield stability of the selected lines of yardlong beans and to identify the best environments for yield selection using the GGE biplot method.

Materials and methods

The yardlong bean genotypes used in the experiment included six selected lines, two parental lines, and two trade cultivars. They were grown in a randomized complete block design, with 3 replicates under 9 environmental conditions. In each environment, there were 30 planting plots. Each plot (experimental unit) contained 24 plants per plot (2 plants per hill), a plot size of 1 × 3 sqm, 2 rows, and 50 x 75-cm spacing (hill x row). The yardlong beans were planted in a plot covered with plastic mulch under a bamboo stake-supported trellising system. Fresh pods were harvested and weighed from each plot every other day for 4 weeks and calculated as yield per hectare (t/ha). The environmental conditions were modified with different planting locations, planting dates, and fertilization, as shown in Table 1.

Table 1. The ten genotypes of yardlong beans were studied for stability in nine modified growing conditions

Locations (Province)	Latitude, Longitude	Planting Dates	Fertilizer applications[1/]	Code of env.
Chonburi	13.231398, 100.956452	Jan 13, 2020	Chemical fertilizers	E1
Chonburi	13.231366, 100.956468	Jan 13, 2020	Cow manure	E2
Chonburi	13.231484, 100.956396	Apr 30, 2020	Chemical fertilizers	E3
Chonburi	13.231333, 100.956481	Apr 30, 2020	Cow manure	E4
Chonburi	13.231513, 100.956496	Jul 30, 2020	Chemical fertilizers	E5
Chonburi	13.230927, 100.955979	Jul 30, 2020	Non-fertilizer	E6
Chonburi	13.231342, 100.956529	Nov 23, 2020	Chemical fertilizers	E7
Chanthaburi	12.753172, 101.863849	Nov 28, 2020	Chemical fertilizers + Cow manure + bio-extract	E8
Uthaithani	15.433268, 99.982110	Dec 19, 2020	Chemical fertilizers	E9

[1/] chemical fertilizers include: 15-15-15 (N-P-K) 500 kg/ha and 46-0-0 (N-P-K) 125 kg/ha; cow manure 11.13 t/ha; bio-extract from durian blossoms, 225 ml/l, sprayed once a week.

Fresh pods were harvested from each plot, and the weight was recorded every other day for 4 weeks to calculate yield per hectare (t/ha). Yield data (t/ha) of 9 environments were analyzed for combined analysis of variance using Statistical Tool for Agricultural Research (STAR) software version 2.0.1

(International Rice Research Institute, 2014b). Genotype and genotype x environment (GGE) biplot analyses were performed using Plant Breeding Tools (PBTools) software version 1.4 (International Rice Research Institute, 2014a). GE scores, which are the inner-product property of the GGE biplot, were calculated by multiplying the genetic principal component matrices (PC1 and PC2) with the environment principal component matrices (PC1 and PC2) as described by Jompuk (2016). Genotype codes were used for analyses and results as follows: G1 = BP Purple; G2 = Bangpra2; G3 = Lamnamch; G4 = Tarntong; G5 = No.1; G6 = No.17; G7 = No.18; G8 = No.25; G9 = No.30; G10 = No.33.

Results

Analysis of variance and the interaction partition

The analysis of variance and the interaction partition according to the GGE biplot analysis of 10 yardlong bean genotypes were displayed in Table 2. The environments (E), genotypes (G), and genotypes by environments interaction (GEI) were highly significant ($p < 0.01$), and they explained 77.68, 4.30 and 8.58 % of the total variation. The first two principal components according to the GGE biplot analysis were highly significant ($p < 0.01$) and accounted for 84% of the total genotype+genotype by environment interaction sum of squares, showed the importance of the first two main components for the yield data.

GE scores of genotypes

The most stable varieties had the most positive sum of GE scores. Therefore, from Table 3, G2 had the highest positive GE scores in environments 1, 2, 3, 4, 5, and 7 and also had the highest sum of GE scores across all environments (17.67), indicating that it is the genotype with the most stability in yield. The next most stable genotypes were G8 and G9, with the 2nd and 3rd highest total GE scores (12.28 and 10.32, respectively). These two genotypes also had positive GE scores in environments 1, 2, 3, 4, 5, and 7.

Relationship between genotypes

The relationship between genotypes was demonstrated by the angle between the two genotypes in Figure 1. It was found that G2, G8, and G9 responded to environments in the same direction, but the responses of these 3 genotypes were in the opposite direction from G3 and G4.

Table 2. Analysis of variance for yield (t/ha) of 10 yardlong bean lines/cultivars under 9 environmental conditions, including the interaction partition based on the GGE biplot method

Source	df	MS	% SS	% PC Explained
Environment (E)	8	872.9736**	77.68	
Block/Env.	18	6.0430 ns		
Genotype (G)	9	42.9128**	4.30	
G x E	72	10.7190**	8.58	
PC1	16	50.6477**		70.00
PC2	14	11.5906**		14.00
PC3	12	8.7803*		9.10
PC4	10	3.6950ns		3.19
PC5	8	2.6317ns		1.82
PC6	6	2.2123ns		1.15
PC7	4	1.3648ns		0.47
PC8	2	1.5370ns		0.27
Pooled Error	162	4.5648ns		
Total	269			

PC = Principal Component
ns, * and ** stand for non-significant, significant at $p < 0.05$ and 0.01, respectively.

Table 3. GE scores for yield of 10 yardlong bean lines/cultivars under 9 environmental conditions

	Environments									Total
	E1	E2	E3	E4	E5	E6	E7	E8	E9	
G1	-3.52	-1.76	-4.00	-1.77	-0.93	0.30	-1.45	0.65	0.13	-12.33
G2	**2.65**	**1.70**	**5.24**	**4.51**	**2.66**	-0.80	**2.56**	0.10	-0.95	**17.67**
G3	1.18	-0.12	-2.91	-5.47	-3.42	**0.98**	-2.33	-1.34	**1.57**	-11.87
G4	-0.26	-0.71	-3.79	-5.11	-3.14	0.91	-2.42	-0.88	1.34	-14.06
G5	-1.37	-0.54	-0.72	0.50	0.37	-0.09	-0.01	0.47	-0.27	-1.66
G6	-0.19	0.07	0.76	1.29	0.80	-0.23	0.57	0.29	-0.36	2.99
G7	-3.44	-1.49	-2.54	0.23	0.30	-0.05	-0.50	**1.00**	-0.40	-6.89
G8	2.20	1.30	3.71	2.84	1.65	-0.50	1.71	-0.09	-0.55	**12.28**
G9	1.82	1.08	3.11	2.41	1.40	-0.42	1.44	-0.06	-0.47	**10.32**
G10	0.94	0.48	1.13	0.56	0.30	-0.10	0.43	-0.16	-0.06	3.52
Total	17.55	9.26	**27.90**	**24.71**	14.97	4.39	13.41	5.04	6.08	

Note: G1 = BP Purple; G2 = Bangpra2; G3 = Lamnamch; G4 = Tarntong; G5 = No.1; G6 = No.17; G7 = No.18; G8 = No.25; G9 = No.30; G10 = No.33

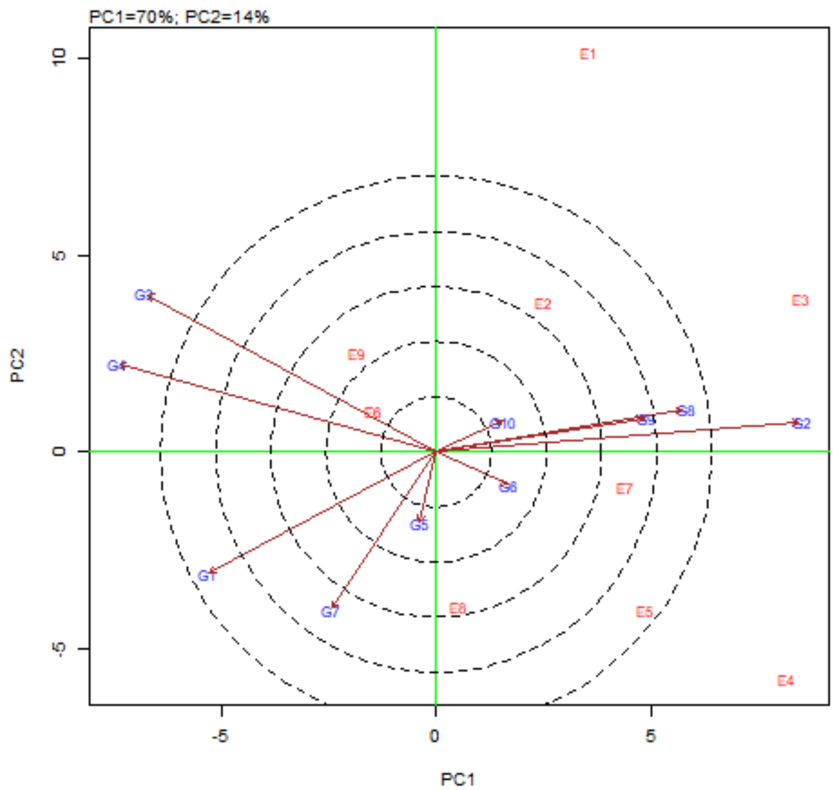

Figure 1. The genotype-vector perspective of the GGE biplot demonstrates similarities in genotypes' responses to various environments

Note: G1 = BP Purple; G2 = Bangpra2; G3 = Lamnamch; G4 = Tarntong; G5 = No.1; G6 = No.17; G7 = No.18; G8 = No.25; G9 = No.30; G10 = No.33

The ideal genotype

The findings showed that the genotypes were divided into two groups (above and below the average) by a line vertical to the average environment axis (AEA). G2, G8, G9, G10, and G6 were among the genotypes which determined to be above average and were recognized as high-yielding genotypes. The genotypes G5, G7, G3, G1, and G4 were determined to be below average and produced the poor yields. The GGE biplot analysis proposed G2 as the best genotype because it was located in the optimum genotype ring center. The other genotypes found in close proximity within the encircling rings were G8 and G9, respectively (Figure 2).

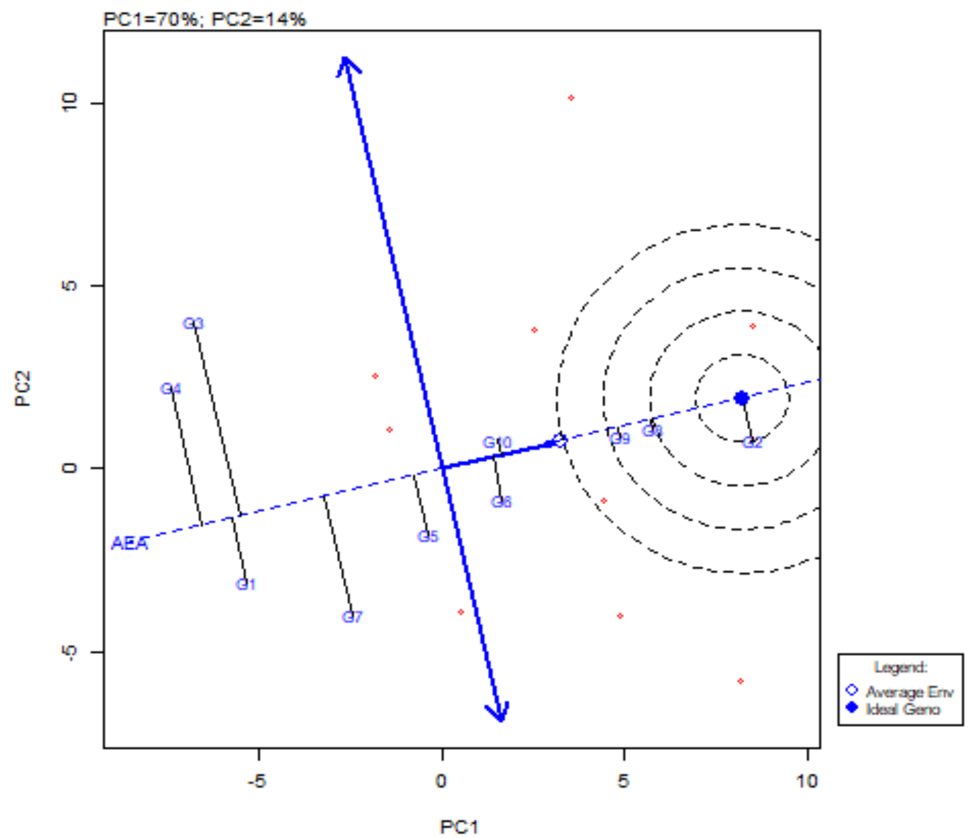

Figure 2. Average environment axis (AEA) view to rank genotypes according to their yield performance compared to an ideal genotype using GGE biplot technique

Note: G1 = BP Purple; G2 = Bangpra2; G3 = Lamnamch; G4 = Tarntong; G5 = No.1; G6 = No.17; G7 = No.18; G8 = No.25; G9 = No.30; G10 = No.33

GE scores of environments

Result showed the total GE scores for environments, which are obtained by summing the GE scores of all genotypes in each environment, regardless of whether they are positive or negative (absolute value) as seen in Table 3. The total GE scores of the environments were values that indicate the potential discrimination of plant genotypes in each environment. Therefore, E3 had the highest total GE score (27.90) which the environment was the highest potential for discriminating yardlong bean genotypes, and followed by E4 (24.71).

The ideal environment

The average environment axis (AEA) expresseed both the mean and stability parameters of all environmental conditions (Figure 3). The small concentric circle designated the ideal location and the arrow points toward AEA. The GGE biplot indicated that E3 was positioned to be the nearest center of the concentric circle, which is an ideal environment, and the angle between its vector and AEA was the lowest, indicating that E3 was considered as the most suitable environment for evaluating genotype stability. Another environmental condition discovered adjacent to the concentric rings was E4 (Figure 3).

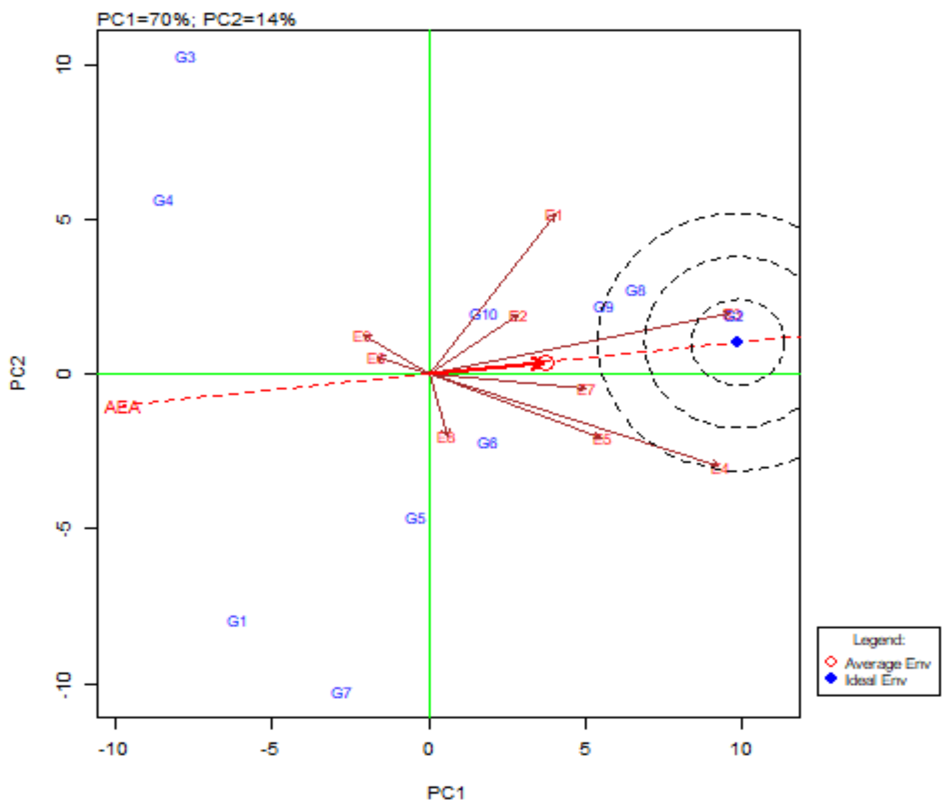

Figure 3. The discrimination and representativeness view of the GGE biplot to rank test environments relative to an ideal test environment (represented by the center of the concentric circles)

Note: G1 = BP Purple; G2 = Bangpra2; G3 = Lamnamch; G4 = Tarntong; G5 = No.1; G6 = No.17; G7 = No.18; G8 = No.25; G9 = No.30; G10 = No.33

Relationship between test environments

The relationship between the vectors was notably positive when the cosine of the angle between the environmental vectors is acute (< 90 degrees), whereas the association is strongly negative when the angle between the vectors is obtuse (>90 degrees). E1 vs E2, E4 vs E5, and E6 vs E9 were therefore considered to be environments with a high positive relationship, E3 vs E6 and E9, E7 vs E6 and E9, E4 vs E6 and E9, E5 vs E6 and E9, and E8 vs E6 and E9 were regarded to be high negatively related. In contrast, E1 vs E5 would be considered as unrelated one because their vector angle were approximately 90 degrees (Figure 3).

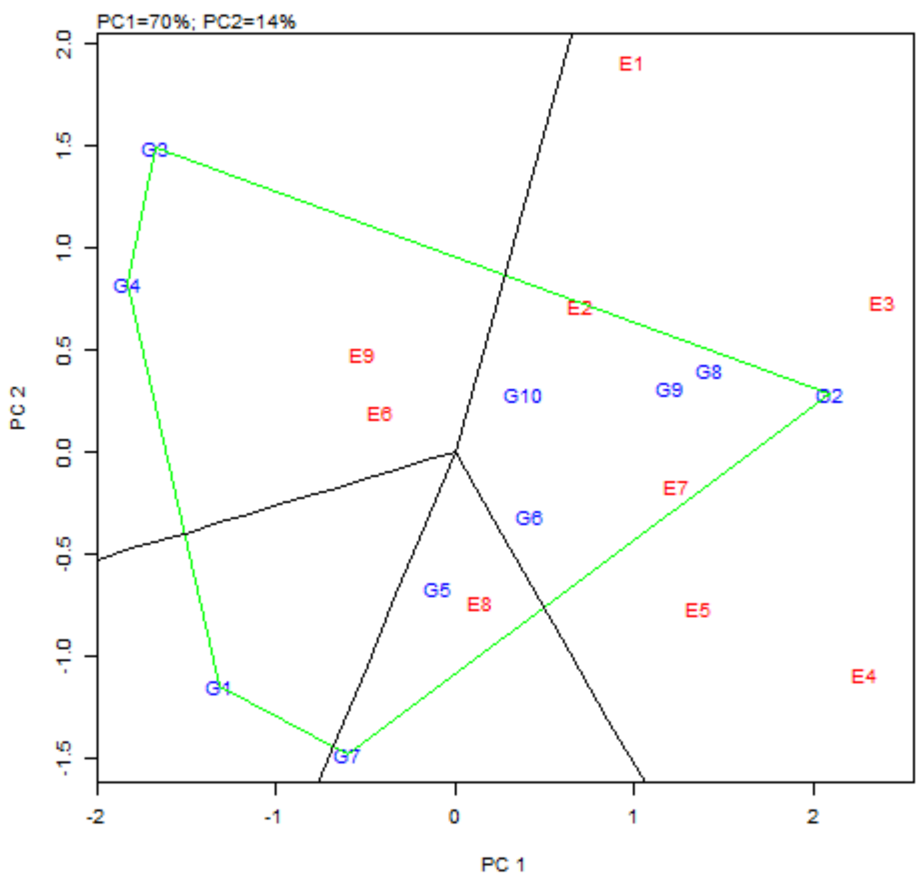

Figure 4. The GGE biplot's which-won-where view demonstrates which genotypes of yardlong beans expressed best in which circumstances

Note: G1 = BP Purple; G2 = Bangpra2; G3 = Lamnamch; G4 = Tarntong; G5 = No.1; G6 = No.17; G7 = No.18; G8 = No.25; G9 = No.30; G10 = No.33

Identification of the megaenvironment

A pentagon was obtained by connecting the positions of genotypes that were further from the beginning of the biplot than other genotypes surrounded by the pentagon (Figure 4). The apex genotypes of the pentagon were G2, G3, G4, G1, and G7. Radial lines are lines vertical to the sides of the pentagon, each dividing the genotype biplot into 4 sections and the environment into 3 sections. The successful genotype is the one located at the corresponding vertex for each environmental sector. Therefore, G2 was the winner in mega-environment including E3, E7, E2, E5, E4, and E1, and it performed the best in E3. G3 was the winner in mega-environment including E9 and E6, whereas G7 was suitable and performed the best in E8. The G1 genotype sector was the only sector that did not contain any environments, indicating that it was not suitable for any of the environments in this study.

Discussion

Analysis of variance and the interaction partition

The environmental variability was very high, indicating that yardlong bean yield was high influenced by environmental conditions because the test plots differed in various aspects, such as growing season, fertilization, and planting areas. The variance of GEI was almost twice as high as that of G, demonstrating the presence of different mega-environments with genotype ranks that differ from those of other mega-environments (Yan *et al*., 2000). Yardlong bean yield had the lowest genotypic influence, consistent with the results of Asfal *et al*. (2012) in mung beans, Pornsuriya *et al*. (2017) in yardlong beans, and Sriwichai *et al*. (2021) in winged beans, indicating that yield was mostly influenced by environment, and followed by genotype by environment interaction which revealed the adaptation of the lines and cultivars to various conditions, while the influence of genotype had the least effect.

GE scores of genotypes

Genotypes that perform well in an environment will be positive GE scores in that environment. Additionally, GE scores can indicate high-yielding and stable genotypes by considering the sum of GE scores from all environments. The GE scores of G2, G8, and G9 were also consistent with the GGE biplot which the graph was plotted between PC1 and PC2, where the best genotypes were more PC1 scores (high yield ability) and should have small PC2 scores (high yield stability) as stated by Yan (1999) and Yan *et al*. (2000). Therefore, it was found that G2 was the most stable in yield, followed by G8 and G9, respectively.

Relationship between genotypes

The angle between the two genotypes shows how similarly they respond to various environments. An acute angle means that two genotypes respond similarly to different environments, and the difference between them is proportional across environments. An obtuse angle denotes that the responses of the two genotypes were opposited. A right angle implies that the two genotypes respond to the environments independently (Yan and Tinker, 2006). Therefore, it was found that G2, G8, and G9 responded to environments in the same direction, indicating that they had a highly positive relationship.

The ideal genotype

The average PC1 and PC2 scores for the main component of the axis for nine environmental conditions were used to create the "mean vs. stability" GGE biplot. The deviation of the projectile line of a genotype from the average environment axis (AEA) indicated the instability of the genotype. In contrast, genotypes with yields that are more stable and closer to the AEA line (Yan, 2001; Yan *et al*., 2007). Therefore, G2, G8, G9, G10, and G6 were discovered as consistent and high-yielding genotypes. However, the GGE biplot analysis proposed G2 as the best genotype because it was located in the optimum genotype ring center. An ideal genotype would have high-yield productivity and stable performance under various environmental conditions (Kaya *et al*., 2006; Yan and Tinker, 2006).

GE scores of environments and the ideal environment

The total GE scores for environments were consistent with the interpretation of the biplots, where E3 and E4, their vector lengths positioned far from the origin, were related to the environments with a high ability to classify genotypes (Yan *et al*., 2000). According to Yan and Tinker (2006), any environmental vector that makes an acute angle to the AEA is taken to be the standard location for all other locations under investigation. E3 was considered the most suitable environment for evaluating genotype stability. This result confirms the findings of Yan *et al*. (2000) and Akinyosoye (2022), who concluded that the location nearest to the circle point is a perfect environment for selecting stable cultivars.

Relationship between test environments

Evaluating the relationship between test environments is useful in planning plant variety testing in different environments. In cases where two environments have a very high positive correlation, it may be worth considered for testing in a single environment, which will produce similar results (Yan and Kang, 2003). The connections between the examined environments are displayed in the GGE biplot's vector view. The cosine of the angle between the environment vectors indicates the relationships between the vectors. (Yan, 2001; Yan, 2002; Yan *et al.,* 2007).

Identification of the megaenvironment

One of a GGE biplot's most noteworthy features is its ability to show the which-won-where structure of a genotype by environment information (Yan and Tinker, 2006). The "which-won-where" or polygonal graph of the GGE biplot identified the top-performing genotype/genotypes for yield for each environmental condition and set of environmental conditions. As a result, G2 won in the mega-environment, which included E3, E7, E2, E5, E4, and E1, and it performed the best in E3.

Acknowledgments

The Agricultural Research Development Agency (Public Organization) (ARDA) is gratefully acknowledged by the research team for providing support for this study (Grant Agreement No. PRP6305030250). We would also like to thank all those involved and all agencies for helping to make this research successful.

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(Received: 27 September 2023, Revised: 14 December 2023, Accepted: 22 December 2023)