PAB
Pesquisa Agropecuária Brasileira

ISSN 1678-3921

Journal homepage: www.embrapa.br/pab

For manuscript submission and journal contents, access: www.scielo.br/pab

Genetics/ Original Article

GGE biplot analysis of the adaptability and stability of wheat genotypes in Mozambique

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Received
July 22, 2023

Accepted
October 19, 2023

How to cite
DIQUE, J.E.L.; MIGUEL, M.A.; PEDRO, C.; SILOTA, G.; FERNANDO, C.J.J.; BUNGALA, L.T. da C.; CHARIMBA, A.M.; ABÍLIO, L.C.; SIMBE, J.D.; CARNEIRO, V.Q. GGE biplot analysis of the adaptability and stability of wheat genotypes in Mozambique. **Pesquisa Agropecuária Brasileira**, v.58, e03549, 2023. DOI: https://doi.org/10.1590/S1678-3921.pab2023.v58.03549.

Abstract – The objective of this work was to use the GGE biplot method to select superior wheat genotypes for adaptability and stability, and to determine grain yield in Sussundenga, Bárué, and Lichinga, in Mozambique, in the 2018/2019, 2019/2020, and 2020/2021 crop years. Eleven treatments were evaluated, using ten wheat genotypes from International Maize and Wheat Improvement Center and a control cultivar developed by a Zimbabwean seed company and used in the national wheat program of the country. Grain yield was the main trait evaluated through individual and joint analyses of variance, adaptability, and stability. The effects of genotypes and the genotype × environment interaction were significant. The adaptability and stability analysis using the GGE biplot method showed that the first two main components explained 94.6% of the total variation for year effect, and 91.8%, for the location effect. The following genotypes can be selected for favorable and unfavorable environments: G1, considered ideal due to its high mean yield and stability over the years; and G4 and G7, for simultaneously showing a high yield and stability over the years.

Index terms: *Triticum aestivum*, genotype x environment interaction.

Análise GGE biplot quanto à adaptabilidade e estabilidade de genótipos de trigo em Moçambique

Resumo – O objetivo deste trabalho foi usar o método GGE biplot, para selecionar genótipos de trigo superiores quanto à adaptabilidade e à estabilidade e determinar a produtividade de grãos em Sussundenga, Bárué e Lichinga, em Moçambique, nas safras agrícolas de 2018/2019, 2019/2020 e 2020/2021. Foram avaliados 11 tratamentos, tendo-se utilizado dez genótipos de trigo provenientes do International Maize and Wheat Improvement Center e uma cultivar testemunha, desenvolvida por uma empresa zimbabweana de sementes e usada no programa nacional de trigo do país. A produtividade de grãos foi a principal característica avaliada, por meio de análises individuais e conjuntas de variância, adaptabilidade e estabilidade. Os efeitos dos genótipos e da interação genótipo × ambiente foram significativos. A análise de adaptabilidade e estabilidade pelo método GGE biplot mostrou que os dois primeiros componentes principais explicaram 94,6% da variação total para o efeito ano, e 91,8%, para o efeito localização. Os seguintes genótipos podem ser selecionados para ambientes favoráveis e desfavoráveis: G1, considerado ideal devido sua alta média de produtividade e estabilidade ao longo dos anos; e G4 e G7, por apresentarem, simultaneamente, alta produtividade e estabilidade ao longo dos anos.

Termos para indexação: *Triticum aestivum*, interação genótipo x ambiente.

Introduction

Wheat (*Triticum aestivum* L.) is one of the first species cultivated in the world together with corn (*Zea mays* L.)and rice (*Oryza sativa* L.) (Takeiti, 2015). It originated from the crossing of wild grasses that existed near the Tigris and Euphrates rivers (Silva et al., 2000; Silva et al., 2015). The composition of proteins present in wheat grains makes it the cereal of greatest importance for human nutrition, since through the baking process it became a cereal consumed worldwide (Joshi et al., 2007; Litoriya et al., 2018; Duarte et al., 2021).

This crop has an important role in the economic and nutritional aspects of human food consumption, as its flour is widely used in the food industry for the manufacture of bread, cakes, cookies, cereal bars, macaroons, and pizza dough, among other uses (Ferreira, 2003; Battenfield et al., 2016; Zamaratskaia et al., 2021). In addition to the importance of the above mentioned reasons, in developing countries, as in most of southern Africa, wheat has been used as a self-sustaining crop for the well-being of the rural family, through the sale of the surplus after harvest on a small scale, using barter with other products of local interest.

Wheat is a cold season crop, whose production conditions allow of only one harvest in Mozambique, with the ideal planting period from April 15 to May 15 (Moçambique, 2021). Crop production in Mozambique remains low, in comparison with those of other countries, due to factors such as the lack of cultivars adapted to the diverse conditions of the country, the use of old cultivars with low productivity, and biotic and abiotic factors (Moçambique, 2021). In addition, wheat production is heavily dependent on the availability of irrigation schemes, as it is planted by the end of the rainy season, thus, crop production in Mozambique is rainfed with little irrigation systems available to most farmers.

Cachomba (2010) reports that the production of wheat in Mozambique is concentrated in the following regions (Tsangano, Sussundenga, and Lichinga), where the production is on average 5% of its annual domestic demand, with grain productivity that does not exceed 1,200 kg ha^{-1}. However, these results are far below the levels required to meet the needs of the country, continuing to entail high costs with imports. The effective cultivation of either a species or a specific cultivar in an agroclimatic region depends on its adaptability, stability, and grain yield (Fayeun, 2018). For and effective cultivation, the adaptability and stability of genotypes should be evaluated, if the presence of genotype and environment interaction (G×E) is possible. Branquinho et al. (2014) report that G×E is responsible for variations in the performance of genotypes in different growing environments, and it is a great challenge for the selection and recommendation of cultivars.

Among the methodologies that have adequately elucidated the main effects and their interactions, the GGE-biplot has shown explanatory and easy-to-understand results. However, this methodology is more effective when there is a more powerful interaction, and it presents an elegant way to visualize data from multi-environment trials and genotype-environment interactions (Yan et al., 2000; Yan & Kang, 2002; Yan & Tinker, 2006; Yan, 2016).

Testing genotypes in multiple environments helps with the identification of cultivars with broad adaptation and specific to specific environments (Noerwijati et al., 2014). Therefore, it is important to carefully define the agricultural subregions that show homogeneous conditions and the most productive genotypes, with broad and specific adaptability, and high stability. This makes it possible to reduce risks in the agricultural system and to advise producers on the best cultivars and their respective environments.

The objective of this work was to use the GGE biplot method to select superior wheat genotypes for adaptability and stability, and to determine grain yield in Sussundenga, Bárué, and Lichinga, in Mozambique, in the 2018/2019, 2019/2020, and 2020/2021 crop years.

Materials and Methods

The experiments were conducted at the research unities of the Instituto de Investigação Agrária de Moçambique (IIAM), in the Centro Zonal Centro and Centro Zonal Noroeste, under irrigation conditions over three crop years (2019, 2020, and 2021), using gravity irrigation at all sites. Geographically, the study sites are in the districts of Sussundenga and Bárué, both in Manica province, and the third site is at Matama farm located near the district of Lichinga, in Niassa province. According to MAE (Moçambique, 2014), Lichinga has red clay soils (Rhodic ferralsols), and shows temperatures between 18 and 24°C. The district of Bárué has alluvial, clayey soils with shallow moderation, with a temperature ranging from 20 to 26°C. In contrast, Sussundenga has lithosols, ferralsols, and fluviosols, with a temperature ranging from 20 to 28°C, according to the Köppen-Geiger's classification.

The experiments were carried out considering a combination of sites and agricultural years, in the total of nine growing environments. The descriptions of the environments, crop years, evaluation sites, and geographical coordinates are presented (Table 1), according to Moçambique (2014).

The genetic material consisted of 10 wheat genotypes from the International Maize and Wheat Improvement Center (CIMMYT, Mexico, and of a locally grown wheat cultivar called Nduna, developed by Seed-Co, which is a Zimbabwean seed company. This cultivar is employed by the national wheat program and it was used in the present research as a control (check). The choice of Nduna cultivar was based on its agronomic characteristics and productive potential, in comparison with the other cultivars of the program (Moçambique, 2021).

The experiment performed in a randomized complete block design, with three replicates. Such genotype occupied an area of 9 m^2, whose useful area had dimensions of 5.0x1.8 m. Each plot consisted of 6 rows spaced at 0.3 m between rows. Each block measured 99 m^2 and contained 11 treatments. In total, the trials occupied 392.7 m^2 area. Planting was done by hand, in early May of each crop year (2019, 2020, and 2021), at all the experiment sites. During planting, 150 kg ha^{-1} of base fertilizer in the formulation of 14-28-14 were applied to stimulate rooting. For topdressing, 150 kg ha^{-1} of urea (46% N) were applied as fertilizer. Sanitary control was performed with applications of pesticides and fungicides, in addition to cultural practices when necessary. Cultivation and phytosanitary control were carried out as recommended in the literature on agronomic management of wheat crops (Reunião…, 2020).

The crop was harvested after it had reached the physiological maturity, which occurred between 100 and 135 days after planting, when plants had more than 90% dry panicles and almost all the leaves were yellow in all the experimental sites. Grains were dried in the sun for four days, followed by tracing, cleaning, weighing, and then stratifying the amount (kg ha^{-1}). Grain yield was determined based on the grain yield of the three median rows of the useful area of each plot, and it was adjusted to grain mass at 13% moisture (converted to kg ha^{-1}).

For the evaluation of the genetic parameters, the individual variances were analyzed using the statistic Genes software (Cruz, 2016), to confirm the existence of genetic variability among the genotypes for the evaluated character, and to joint consider the fixed genotype effect and random environment effect, according to the following equation:

$$Y_{ijk} = m + (B/L)/A_{jkm} + G_i + A_j + L_k + GA_{ij} + GL_{ik} + AL_{jk} + GAL_{ijk} + E_{ijk},$$

where: Y_{ijk} is the observation in the k^th^ block, evaluated on the i^th^ genotype and j^th^ environment; m is the general test constant; $(B/L)/A_{jkm}$ is the effect of blocks within years within locations; G_i, A_j, and L_k are the effect of genotypes, crop years, and locations; GA_{ij}, GL_{ik}, and AL_{jk} are the effect of first-order interactions between genotypes and years, genotypes and sites, and sites and years; GAL_{ijk} is the effect of blocks within

Table 1. Geographical coordinates of locations where the trials of 11 wheat (*Triticum aestivum*) genotypes were conducted in 2019, 2020, and 2021 crop years, in Mozambique.

Environment	Agricultural year	Location	Latitude S	LongitudeW	Altitude (m)
E_1	2018/2019	Sussundenga	19°30'141"	032°54'620"	913
E_2	2018/2019	Bárué	18°78'98896"	33°17'4735932"	522
E_3	2018/2019	Lichinga	13°19'569"	35°15'056"	814
E_4	2019/2020	Sussundenga	19°30'141"	032°54'620"	913
E_5	2019/2020	Bárué	18°78'98896"	33°17'4735932"	522
E_6	2019/2020	Lichinga	13°19'569"	35°15'056"	814
E_7	2020/2021	Sussundenga	19°30'141"	032°54'620"	913
E_8	2020/2021	Bárué	33°17'4735932"	33°17'4735932"	522
E_9	2020/2021	Lichinga	13°19'569"	35°15'056"	814

years within locations; and E_{ijk} is the random error. All effects, except for that of the environment, were considered fixed.

Then, the adaptability and phenotypic stability of the genotypes were studied using the GGE biplot methodology, which considers the effect of the genotype and the interaction between the genotype and environment (Yan et al., 2000). The GGE biplot analysis was performed following the statistical model below:

$$Y_{ij}-Y_j=\lambda_1\varepsilon_{i1}\rho_j+\lambda_2\varepsilon_{i2}\rho_{j2}+\varepsilon_{ij}$$

where: Y_{ij} is the response value of the j observation (j = 1, ..., n) at the ith factor level (i = 1, ..., a); Y_j is the average yield over all genotypes in the environment; λ_1 and λ_2 are the largest eigenvalues of the first (PCA1) and second (PCA2) principal components, respectively; ε_{i1} and ε_{i2} are the eigenvalues of genotype i for PCA1 and PCA2, respectively; and ρ_{j1} and ρ_{j2} are the eigenvalues of the environment j for PCA1 and PCA2 (Yan & Rajcan, 2002; Yan & Tinker, 2006). This methodology does not separate the effects of genotype and interaction (GxE), keeping them together in two multiplicative terms (Yan et al., 2000; Fritsche-Neto et al., 2010). Thus, it was used to facilitate the visualization and interpretation of the obtained data, where genotypes can be evaluated for their performance in each environment, or in different evaluation environments to inform specific or broad adaptation (Mohammadi & Amri, 2012).

The comparison of the means was performed using the mean grouping test, proposed by Scott-Knott (1974), at 5% probability. Finally, with the presence of interaction between genotypes and environments, there was the need to perform the GGE biplot analysis, to identify the more adapted and stable genotypes in each environment for selection.

Results and Discussion

The results obtained from the joint analysis of grain yield of the 11 genotypes used in this research show significant effects regarding their interaction with the tested environments (Table 2). From the results, it is possible to notice a differential performance in the interaction between the genotypes, environments, and the seasons of evaluation, once the weather condition of one season showed a difference from another season, as well as water availability of each location differed from the other location, thus becoming a limiting factor for decision making.

In a study on wheat genotypes, the factor effects of the agroclimatic conditions influenced the productive potential of the genotypes, which resulted in differential behavior of these genotypes over the years, according to Felicio et al. (2008). However, in the present research, after the joint analysis, the coefficient of experimental variation displayed a magnitude of 15.99%, which can be considered compatible with those observed for the character associated with grain yield, with quantitative inheritance, and which were highly influenced by the environment (Falconer & Makai, 1996; Pimentel-Gomes, 2009). The success of new cultivars launched in the market depends on their characteristics and their agronomic performances, in addition to the interaction between the genotypes and the environment in the cultivation area (Nörnberg et al., 2014). However, the presence of interaction between genotypes and environments hinders the selection and recommendation of cultivars (Silva et al., 2011, 2015). In this sense, it is necessary to perform more accurate evaluations to identify more adapted genotypes (Silva et al., 2015, 2021).

The average grain yields of the 11 wheat genotypes are presented (Table 3). The greater variation for grain yield is attributed to the reduction of the amount of water supplied to the experiments, due to its insufficient source, especially between September and October,

Table 2. Analysis of variance for grain yield evaluated in 11 wheat (*Triticum aestivum*) genotypes, in nine environments in Mozambique (Sussundenga, Bárué, and Lichinga), between the 2018/2019, 2019/2020, and 2021 crop years.

Source of variation	Degree of freedom	Mean square
(B/L) /A	18	13,408,867.79
Genotype (G)	10	4,380,969.31*
Crop years (Y)	2	27,336,250.56**
Locations (L)	2	193,772,050.14^{ns}
G x A	20	1,704,986.97**
G X L	20	2,089,953.65*
E X L	40	131,505,079.69**
G XA X L	40	1,000,624.21**
Residue	180	467,000.42
Average (kg ha^{-1})		4,271.48
CV (%)		15.99

^{ns}Nonsignificant. **, *Significant at 1% and t 5% probability, respectively. (B/L) /A, blocks or location within environment. E, environment. GxE, genotype by environment interaction. CV, coefficient of variation.

during the flowering phase of the experiments. These results are supported by findings of Oteros et al. (2015), in which plant phenology was influenced by the climate, mainly by the availability of water and air temperature. When these factors are not optimal for the plant, they can cause different physiological responses, which can alter the ranking of the winning genotypes, thus creating differentiation in the yield results.

The additive and multiplicative interaction effects were grouped by the GGE biplot analysis (Figure 1) and subjected to the principal component analysis (Yan et al., 2000; Yan, 2014). The first two principal components (PC1 and PC2) explained from 31.42 to 63.19%, accounting for 94.61% of the variation for grain yield characteristics, thus enabling good reliability or efficiency of the biplot analysis. Therefore, these results clearly show that the multivariate methodology explained a large proportion of the sum of squares of genotypes and interaction (GxE), showing high efficiency (Santos et al. 2017). For a higher reliability of the GGE biplot analysis, the first two principal components should capture more than 60% of the total variation, according to Yang et al. (2009). However, the which-won-where GGE-biplot (Figure 1 A), obtained from the two principal components, showed a visualization of patterns that allowed of the identification of genotypes with superior performance for the year effect specifically. Mega-environments are defined as a group of subregions that consistently share a single genotype, or a group of similar genotypes, which are specifically adapted and the best in performance (Gauch and Zobel, 1996; Yan & Rajcan, 2002; Yan, 2014). According to Figure 1 A, the polygon starting from the center of the biplot (0,0) has been delimited into five sectors, which pass through the following genotypes: G1, G6, G4, and G9, fixed or present at the vertices. The graphical analysis indicated the existence of two mega-environments: Y1, Y2, and Y3. Years in the same mega-environment are considered similar, concerning the response of the genotypes (Evangelista et al., 2021). The polygonal view of a GGE biplot not only presents the best cultivar for each test environment, but also divides the test years into groups (Yan & Kang, 2002). The vertices of the observed polygons indicate that the genotypes farthest from the origin of the biplot are the ones that perform best in one or more environments (Yan & Kang, 2002; Yan, 2014), therefore, these genotypes are more preferred for recommendation in specific locations. Genotypes G6 and G4 showed better average performance in the mega-environment in crop year (Y1), and G1 and G9 had better average performance in crop years (Y2 and Y3).

The methodology was effective to evaluate the behavior of the genotypes, considering the yield in the years under study (Figure 1 B). Furthermore, the continuous green line with a single arrow, called the "mean environment axis" is defined by the mean coordinate of all test environments in the biplot, and it points to the genotypes that showed the highest mean productive performance. The genotypes G6, G2, G5, and G8 are located above the average, that

Table 3. Average grain yield (kg ha^{-1}) of 11 wheat (*Triticum aestivum*) genotypes evaluated in Mozambique (Sussundenga, Bárué, and Lichinga) in the 2018/2019, 2019/2020, and 2021 crop years(1).

Genotype	Sussundenga			Bárué			Lichinga		
	2019	2020	2021	2019	2020	2021	2019	2020	2021
G1	7543.5Aa	8998.5Aa	2953.8Ca	3711.3Ba	3531.3 Ba	6034.2 Aa	4426.5Ba	3951.6Ba	4873.2Ba
G2	8176.1Aa	7282.1Ab	3088.5Aa	4279.6Ba	2432.0 Bb	3222.2 Ad	3164.3Ba	3131.5Ba	2786.3Ab
G3	5632.1Ab	7169.5Ab	2583.4Ba	4098.3Ba	2447.7 Bb	5415.9 Ab	3231.3Ba	2248.3Bb	2262.1Bc
Nduna(2)	6649.9Ab	5306.2Ac	2285.7Ba	2642.8Ba	2180.9 Bb	5094.2 Ab	3402.7Ba	1356.4Bb	2005.7Bc
G5	8392.8Aa	7520.2Ab	3214.9Ba	3871.9Ba	1617.4Cb	4592.6Ac	3398.6Ba	3150.6Ba	2837.6Bb
G6	8068.5Aa	7448.1Ab	2546.6Ba	4889.1Ba	2502.2Bb	4253.7Ac	3372.6Ca	2780.2Ba	3166.7Bb
G7	8201.7Aa	8021.4Aa	2791.0Ca	3513.2Ba	2429.1Bb	5720.8Aa	3242.2Ba	2241.5Bb	3823.4Ba
G8	7990.9Aa	8128.8Ab	2743.9Ba	3936.1Ba	1792.9Bb	4059.9Ac	3754.6Ba	2283.1Bb	4272.1Aa
G9	5400.8Ab	6763.2Ab	2183.3Ca	3302.7Ba	3211.5Ba	6381.8Aa	3313.5Ba	3417.9Ba	3864.7Ba
G10	6769.4Ab	7053.6Ab	3408.5Ba	4442.2Ba	2914.6Ba	5980.1Aa	2609.7Ca	2773.509Ba	3296.3Bb
G11	7364.1Aa	8222.8Aa	3029.9Ca	3143.2Ba	2246.3Bb	5350.4Ab	30260.3Ba	2992.7Ba	4243.6Ba
Averages/E	7289.930	7446.765	2802.680	3802.770	2482.381	5100.492	3358.360	2757.024	3402.874

(1)Means followed by equal capital letter in the columns, do not differ by Scott-Knott's test, at 5% probability. (1)Control cultivary. E, environment.

is, with higher average productive performance over the years. In contrast, the genotypes G1, G7, G11, G10, G9, G3, and G4 were the least productive ones, with below average performance. The second continuous green line is perpendicular to the environment-media axis, and points to greater stability, thus, the longer is the length of the green line (dotted), the more unstable is the genotype (Yan & Tinker, 2006; Alves et al., 2020), which occurred for the genotype with the lowest performance G6 and G2. Based on the results

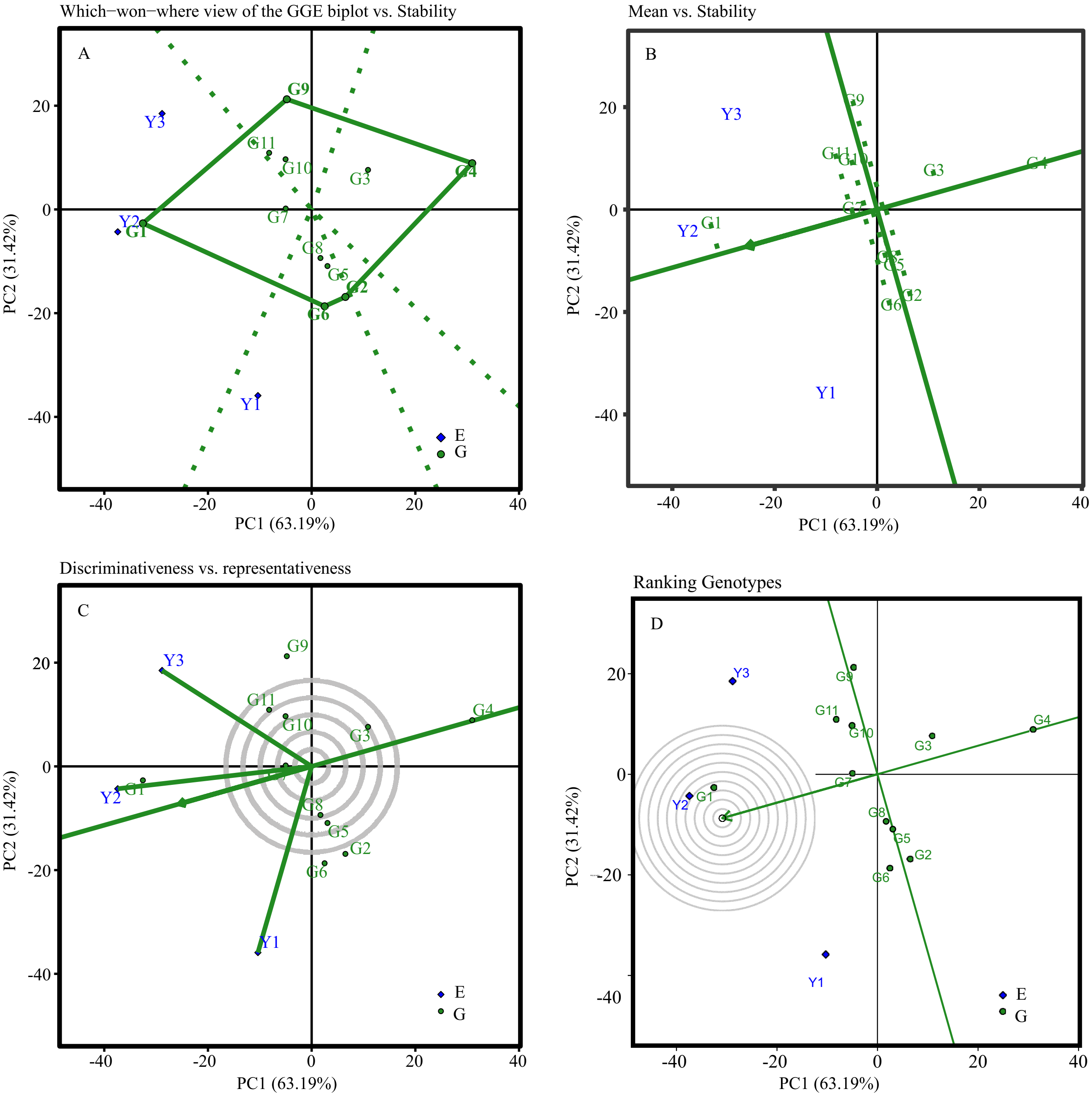

Figure 1. GGE biplot for the grain yield of 11 wheat (*Triticum aestivum*) genotypes (G) in relation to the crop year (Y) variation, in nine environments (E) in Mozambique (Sussundenga, Bárué, and Lichinga), in the 2018/2019, 2019/2020, and 2021 crop years. Y1, Y2, and Y3 are the means of the first, second, and third crop year, respectively.

(Figure 1 B), the G7 and G4 genotypes are indicated for simultaneously exhibiting high-average yield and stability, which is a highly desired association (Yan & Kang, 2002; Yan & Tinker, 2006; Yan et al., 2007; Yan, 2014).

The GGE biplot for "discrimination and representativeness" shows the ideal test environments for selecting superior genotypes (Figure 1 C). The environments with the longest vectors are the most discriminating ones, and those with the shortest vectors are less discriminating ones, providing little or no information on the genotypes, and they can be discarded as test environments or should not be used as test environments (Yan & Tinker, 2006; Hongyu et al., 2015). Thus, the most representative genotypes are those that form a smaller angle between their vectors (discontinuous and continuous blue lines). Therefore, the grain yield in crop years Y2 and Y3 was most discriminating in relation to the genotypes presenting the longest, superior vector, allowing for the behavior differentiation of the genotypes. However, an important aspect that can be observed is the representativeness of the environments, since the smaller the angle of the location vector, in relation to the single arrow axis representing the coordinate of the average environment, the greater is the representativeness of this location in relation to the evaluated set of locations. In this sense, the most representative agricultural year was Y2, that is close to the ideal, as it was more representative for the averages of all years. The other years can be considered discriminating and nonrepresentative, serving to select genotypes with specific adaptation in mega-environments. Discriminating and representative environments are efficient for selecting cultivars with broad adaptation, while discriminating and nonrepresentative environments can be useful for discarding unstable genotypes (Silva et al., 2015).

The graphical criterion "Ranking Genotypes" (Figure 1 D) indicates the genotypes that are closest to the center of the concentric circles, referring to them as the most desirable ones. For this research, the genotypes G1 and G7, out of all 11 evaluated, are the closest ones to a hypothetical ideal genotype. An ideal genotype should have high productivity and high stability in all evaluated environments (Naroui Rad et al., 2013). Yan & Hunt (2002) report that, in only one mega-environment, genotypes are considered stable if they are in the AEC line, and they are considered productive, if the PC is high and positive.

The experiment locations (Figure 2) showed that the additive effect of genotypes and multiplicative effect of interaction were grouped by the GGE biplot analysis; thus, they were subjected to the principal component analysis (Yan et al., 2000; Yan, 2014). The analysis of the first two components (PC1 & PC2) resulted in 31.05 to 60.75% (Figure 2 A), justifying the total capture of 91.8% of the variation for grain yield characteristics, thus enabling a good reliability of the biplot analysis. Therefore, these results clearly show that the multivariate methodology explained a large proportion of the sum of squares of the genotypes and the GxE, showing the high efficiency of the methodology (Santos et al., 2017). Also, Yang et al. (2009) reported that for a higher reliability of the GGE biplot analysis, the first two principal components should capture more than 60% of the total variation. However, the GGE biplot "which-won-where" (Figure 2 A), obtained from the two principal components, showed a visualization of the patterns, allowing of the identification of the genotypes with superior performance for the specific location. According to this graph (red lines) that starts from the center of the GGE biplot (0,0), it was delimited in six sectors by the following genotypes: G1, G9, G4, and G5, and they correspond to those considered more responsive that are present in the vertices. The analysis of the graph indicates the existence of two mega-environments: L1, L2, L3. Sites that contained in the same mega-environment are considered similar, concerning the responsiveness of the genotypes (Alves et al., 2020; Yan, 2014). The polygonal view of a GGE biplot not only presents the best cultivar for each test environment, but also divides the test environments into groups (Yan & Kang, 2002). The genotypes G5 and G4 showed the best average performance in the mega-environment in location (L1), G1 had the best average performance in location L3, and G9 showed the best average performance in location (L2).

In the graph "Mean vs. Stability" (Figure 2 B), the methodology was efficient to evaluate the behavior of the genotypes considering the productivity and the stability in the locations under study. The genotypes G5, G2, G3, G10, G9, and G4, located above the mean, have higher mean productive performance among the sites, while G8, G6, G7, G11, and G1 are lower performers. Based on the results, the G6 and G4 genotypes are indicated because they simultaneously showed high average yield and stability, a highly desired association (Yan & Kang, 2002; Yan & Tinker, 2006; Yan et al., 2007; Yan, 2014).

The optimal test environments by GGE biplot for the identification and selection of superior genotypes should be both discriminative and representative (Figure 2 C). Thus, grain yield in the L1 and L2 locations was the most discriminating about genotypes,

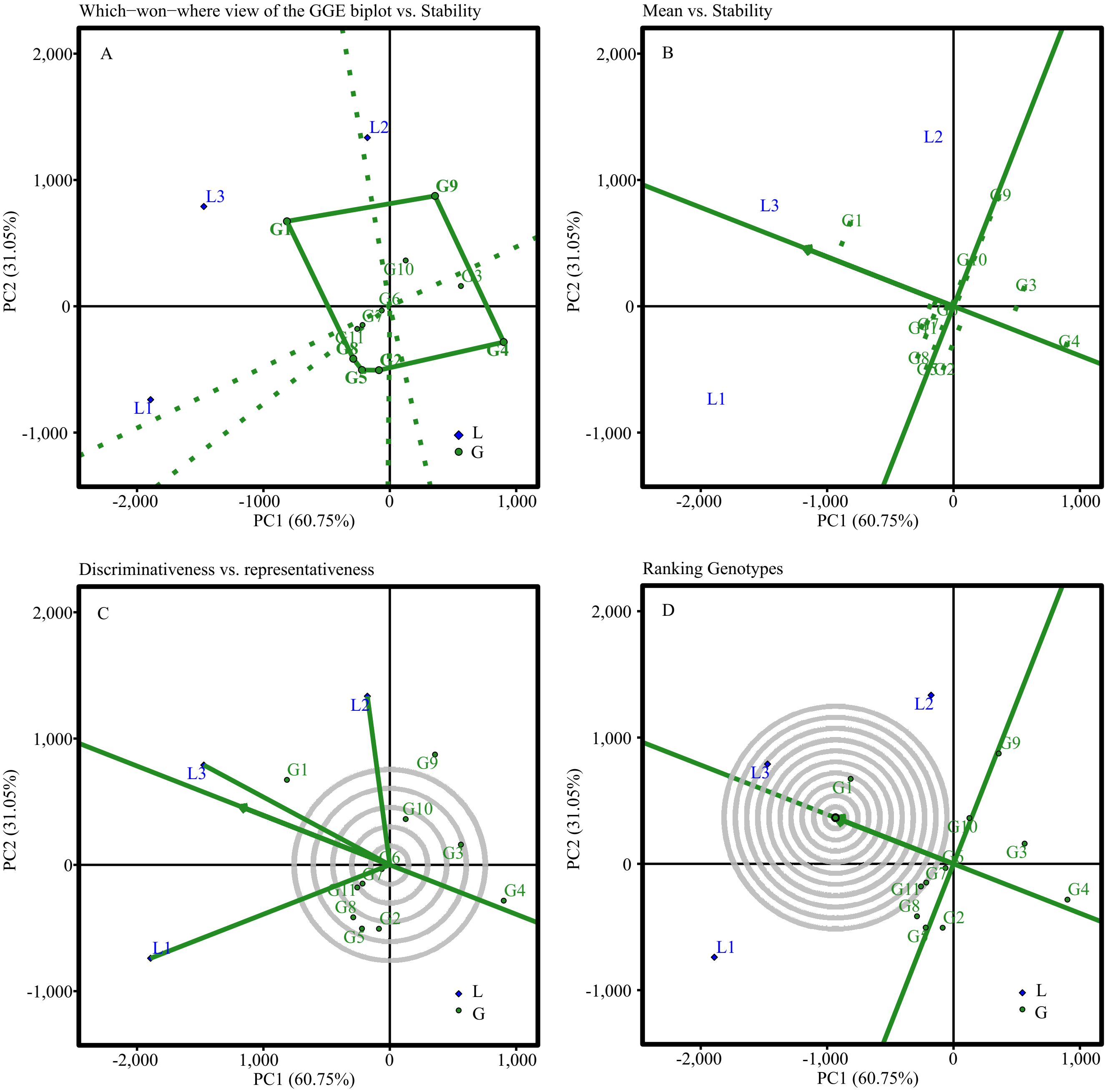

Figure 2. GGE biplot for the yield of 11 wheat (*Triticum aestivum*) genotypes (G) in relation to the Sussundenga, Bárué, and Lichinga locations (L) in Mozambique, in 9 environments (E), in the 2018/2019, 2019/2020, and 2021 crop years. L1, L2, and L3 are the means of the first, second, and third location of the experiments, respectively.

presenting the longest vector, higher, allowing of the behavior differentiation of the genotypes. However, the L3 location is the closest to the ideal, for being the most representative one for the averages of all years (Figure 2 C). The other sites can be considered discriminating and not representative, serving to select genotypes with specific adaptations in mega-environments.

The criterion “Ranking Genotypes” (Figure 2 D) indicates that the genotypes closest to the center of the concentric circles are the most desirable ones. Therefore, G1, among all the 11 genotypes evaluated, is the closest one to a hypothetical ideal genotype. To be considered ideal, a genotype should show a high productive performance associated with high stability (Silva et al., 2021). In GGE biplot analysis, this “ideal genotype” is defined by the vector of greatest length in PC1 (yield), without projections in PC2 (instability), which means to be the closest genotype to the smallest central concentric circle (Silva et al., 2015).

Conclusions

1. It is possible to select wheat (*Triticum aestivum*) genotypes that are superior for adaptability, stability, and grain yield, in the Sussundenga, Bárué, and Lichinga environments of Moazambique.
2. The effects of genotypes, environments, and interaction are significant by the adaptability and stability analyses using the GGE biplot method, showing that the first two principal components explain 94.6% of the total variation for the year effect and 91.8% for the environment effect.
3. The following genotypes can be selected for favorable and unfavorable environments: G1, considered ideal due to its high mean yield and stability over the years; and G4 and G7, for simultaneously showing a high yield and stability over the years.

Acknowledgments

As IIAM researchers, our thanks go to all who have collaborated directly and indirectly to make this research a success; and to Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), for funding the PhD fellowship.

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