Maize Hybrids: Mega-Environments in Java Island, Indonesia

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Abstract

Identification of grain yields on stable and high yielding maize hybrids in a wide environment requires high accuracy. There were many stability measurement methods used in multi-environment experiments. However, the relationship between each measurement was still difficult to understand. The objectives of this study were to: 1. identified the effect of growing season, location, hybrids (genotypes), and their interactions (GEIs) on grain yields; 2. determined the relationship between each stability measurement; 3. selected the stable and high yielding maize hybrids in a wide environment; and 4. determined favorable (discriminativeness) locations for testing. The field experiment was conducted at eight locations in Java island, Indonesia during two seasons used a randomized completed block design with three replications. The experimental results showed that the main effects of growing season, location, hybrid, and GEIs, had a significant effect on maize hybrid yields. Stability measurements $S^{(3)}$, $S^{(6)}$, $NP^{(2)}$, $NP^{(3)}$, $NP^{(4)}$, and CV_i, belong to the concept of dynamic stability that can be used to selected maize hybrids in favorable environments, while other measurements were classified as in the concept of static stability. Two maize hybrids were successfully selected to have high and stable yields based on numerical and visual measurements, namely SC3 and SC9. The two hybrids can be used as candidates for a sustainable maize development program. GJRS and KARS were the most discriminativeness environments. Both can be used as a favorable environment for selecting the ideal maize hybrid.

Introduction

The potential of maize as a high carbohydrate producer makes this commodity amongst the most important of staple foods in Indonesia. Maize also contains other nutrients that are important for the body such as vitamins, proteins, and minerals [1,2]. Currently the demand for maize was increase, but the existing production supply was still unable to fulfill it [3]. One of the causes of low maize production was caused by the influence of environmental conditions of cultivation including agro-climate and cultivation techniques [4]. Given the importance of maize and its potential for cultivation throughout Indonesia, the increased in yields must be taken seriously. Therefore, maize hybrids were needed that have high yields and resistant to environmental changes.

Testing of maize hybrids in various environments and growing seasons was necessary to select grain yield stability. Selection under various environmental conditions is very complex due to the influence of genotype and environmental interactions (GEIs) [5–7]. The emergence of GEIs in multi-environmental experiments are due to unpredictable macro- and micro-environmental influences such as temperature, rainfall, and humidity [8]. According to Karuniawan et al. [9], differences in the growing environment gave different responses for each genotype tested. In addition, genetic background can also have an influence on adaptability to different environments.

There are various measures to describe the effect of GEIs and identify stable genotypes. Some of them were linear regression [10], Wricke ecovalence [11], Shukla variance [12], coefficient of variation (CVi) [13], thennarasu parametric measurement ($S^{(n)}$) [14], Kang rank[15], AMMI [16], and GGE biplot [17]. In determining stable and high yielding genotypes, the use of a single stability measurement was considered less accurate [1,7,18]. The used of various stability measurements was considered quite effective and accurate in determining stable and high yielding genotypes. Several researchers have succeeded in selected stable and high yielding genotypes in a wide environment with various stability measurements, including durum wheat in Turkey [19], barley in Iran [20], sweet corn in Indonesia[1], and sweet potato in Indonesia [9]. Therefore, the use of various stability measurements was used in this study. The main objectives of this study were to identify the effect of growing season, location, hybrids (genotypes), and their interactions (GEIs) on yields; determine the relationship between each stability measurement; select stable and high yielding maize hybrids in a wide environment; and determine the discriminativeness locations for testing.

Materials And Methods

Plant materials: The study used eleven maize hybrids which were the result of plant breeding program, Faculty of Agriculture, Universitas Padjadjaran (UNPAD). The hybrids tested had different genetic backgrounds (Table 7) and high genetic diversity [23].

Field experiments and data collection: Field experiments were conducted at eight locations on the Java Island, Indonesia, during two growing seasons (Table 2). The experiment used a randomized completed block design which was repeated 3 times. Each hybrid was planted at a spacing of 75 x 20 cm. The data was taken at harvest, which is 93 days after planting following the standard Descriptor for Maize[31]. The yield of each hybrid in each experimental plot was converted in $ton.ha^{-1}$.

Data analysis: Combined analysis of variance (ANOVA) was used to estimate the GEIs. The statistical equations used as follows:

$$Y_{opqr} = \mu + G_o + E_p + GE_{op} + R_{q(p)} + B_{r(q)} + \varepsilon_{opqr}$$

where Y_{opqr} is the value of line o in plot r, and the value in location p of each replication q; μ is the grand mean; G_o is the effect of line o; E_p is the effect of the environment p; GE_{op} is the effect of genotype by environment interactions on line o and environment p; $R_{q(p)}$ is the effect of replicate q on location p; $B_{r(q)}$ is the effect of replication q on plot r; and ε_{opqr} is the error effects from line o in plot r and repeat q of location p, respectively. To calculate the combined ANOVA used R program.

Yield stability was analyzed used parametric and non-parametric measurements. The details of the stability measurements used were presented in Table 8. The online software "STABILITYSOFT" was used to estimate the stability of grain yields using parametric and non-parametric measurements [32].

The visual stability of grain yields and determination of discriminative environment was used GGE biplot with the following equation [17]:

$$\bar{\Upsilon}_{mn} - \mu_m = \beta_n + \sum_{k=1}^{t} \lambda_o \alpha_{mo} \gamma_{no} + \varepsilon_{mn}$$

where $\bar{\Upsilon}_{mn}$; μ_m; β_n; k; λ_o; α_{mo} and γ_{no}; ε_{mn} are the performance in location 'n' from line 'm'; overall average grain yield; the influence of location 'n'; number of primer components; the singular value from primer component 'o'; value of line 'm' and location 'n' for primer component 'o'; and the error of the line 'm' in location 'n', respectively.

The R program was used to visualize the distribution pattern of the hybrids and environments tested in the dry season, rainy season, and the average of both.

Spearman rank correlation and Principal Component Analysis (PCA) were used to estimate the relationship between stability measurements and classify them into clear groups. The SPSS 19th software was used to analyze correlation and PCA.

Results

Genotype by environment interactions of maize hybrids yield

The combined ANOVA for maize hybrids evaluated at eight locations during two growing seasons in Java island was presented in Table 1. There was a very significant variation ($p < 0.01$) on yields between hybrids (genotypes), environment (season, location, season × location) and their interactions (Genotype × season, Genotype × Location, and Genotype × season × Location) (Table 1). It was noted that there were a high degree of variability for the average yield in 16 environments, ranging from 7.33 t.ha^{-1} (GJRS) to 11.68 t.ha^{-1} (NNRS) (Table 2). The average data for two growing seasons recorded the highest average yield at Ngronggot, Nganjuk, East Java (9.63 t.ha^{-1}) and the lowest at Paiton, Probolinggo, East Java (7.82 t.ha^{-1}) (Table 2). The significant variation of the main effects and their interactions indicated that there were differences in the hybrid rank of each test environment, this confirmed that there was a significant hybrid based on environmental interactions in this experiment. Therefore, further testing using stability measurements was needed to determine stable maize hybrids.

Yield stability analysis of maize hybrids based on numerical measurements (parametric and non-parametric)

Table 3 presented the results of the stability analysis of maize yields using parametric measurements, and Table 4 using non-parametric measurements. According to Eberhart and Russell's [10], the stability of each maize hybrid was determined used the regression coefficient (bi) and deviation of variance (S^2di), with estimates of $b_i = 1$ and a low S^2di indicating a very stable hybrid (Table 5). The SC2, SC4, SC7, SC9, and SC11 hybrids had b_i values that were not significantly different from one(1), where SC 2, SC 7, and SC 11 produced yields that were lower than the overall average, while SC4 and SC9 were higher than the overall average. S^2d_i estimates SC2, SC6, and SC9 as maize hybrids possessing the lowest values.

According to the principle of linear regression, hybrids with values of $b_i = 1$ and $S^2d_i = 0$ were the most stable, so SC2 and SC9 were the most stable based on this measurement. Average grain yields for the hybrids tested in 16 environments ranged from 7.88 to 10.39 $t.ha^{-1}$, with SC3 and SC10 hybrids having the highest average yields and SC7 and CS11 the lowest (Table 3). In the stability ranking, W_i^2, σ^2_i, s^2d_i, dan $\theta_{(i)}$ measurements declared SC2 as the most stable, followed by SC9 and SC6. Of the three selected hybrids, only SC9 had above-average yields. Cv_i selected SC3 as the most stable followed by SC 1 and SC2. θ_i also stated SC3 as the most stable followed by SC5 and SC1. SC3 was the hybrid with the highest yield performance in all test environments. D_i measurement selected SC4 as the most stable followed by SC11 and SC8, where SC4 and SC8 had above-average overall performance. In non-parametric measurements (Table 4), SC3 hybrids were declared the most stable by measurements of $S^{(1)}$, $S^{(3)}$, $S^{(6)}$, $NP^{(3)}$, and $NP^{(4)}$. The SC6 hybrid was declared the most stable by $S^{(2)}$ measurement. The SC9 hybrid was declared the most stable by $NP^{(1)}$, $NP^{(2)}$, and KR measurements. This hybrid has above-average yield performance.

To classify maize hybrids based on stability ranks from parametric and non-parametric measurements, Hierarchical Clustering Analysis (HCA) was used (Figure 1). Maize hybrids were divided into three main groups, namely 1) unstable high yield cluster containing SC8 hybrids, SC10, SC4, SC1, and SC5. This group can be used as hybrids with high yield performance in specific adaptation; 2) unstable low yield cluster containing SC7 and SC11 hybrids; and 3) a stable high yield cluster containing SC2, SC9, SC6, and SC3 hybrids. This cluster was the most ideal because it has excellent yield performance in a wide environment.

The relationship between numerical measurements on the maize hybrids yield

To determine the relationship between the different stability measures and combined them into clear groups, PCA was used. The first four PCs with eigenvalues >1 resulted in a cumulative value of 92.70% of the total variation between parametric and non-parametric measurements (Table 5). The first two components were used to visualize the PCA biplot because it had the highest variability values (PC1= 41.23% and PC2= 30.61%) and eigenvalues of 7.42 and 5.51, respectively, as shown in Figure 2. Parametric and non-parametric measurements were classified into three main groups, namely: first group contained $NP^{(1)}$, b_i, W_i^2, S^2d_i, $\theta_{(i)}$, and σ^2_i ; second group contained KR, $S^{(1)}$, $S^{(2)}$, and D_i; the third group contained yields (Y) with $S^{(3)}$, $S^{(6)}$, $NP^{(2)}$, $NP^{(3)}$, $NP^{(4)}$, CV_i, and θ_i measurements.

Based on the Spearman rank correlation coefficient, the average yield was positively and significantly correlated with $S^{(3)}$, $S^{(6)}$, $NP^{(2)}$, $NP^{(3)}$, $NP^{(4)}$, KR, and CV_i ($p<0.05$) (Table 6). Other positive and significant correlations were $S^{(1)}$ against $S^{(2)}$ and $S^{(3)}$; $S^{(2)}$ against $S^{(3)}$; $S^{(3)}$ against $S^{(6)}$, $NP^{(2)}$, $NP^{(3)}$, NP(4), and KR; $S^{(6)}$ against $NP^{(2)}$, $NP^{(3)}$, $NP^{(4)}$, KR, and CV_i; $NP^{(1)}$ against W_i2, σ^2_i, s^2d_i, and $\theta_{(i)}$, and negatively correlated to θ_i; $NP^{(2)}$ against $NP^{(3)}$, $NP^{(4)}$, KR, and CV_i; $NP^{(3)}$ against $NP^{(4)}$, KR, and CV_i; $NP^{(4)}$ against KR; W_i^2 against σ^2_i, s^2d_i, and $\theta_{(i)}$; while $\theta_{(i)}$ was negatively and significantly correlated with θ_i.

Mega-environment analysis of maize hybrid yield and identified representative locations using GGE biplot

In the dry season GGE biplot analysis, PC1 explained 47.27% and PC2 explained 19.23% of the total variation, accounting for 66.50% of the total variation for grain yields (Figure 3). The 'which won where/what' pattern showed that eight locations have six sectors with different winning hybrids (vertex). The vertex hybrids were SC3, in JKDS, KADS, GJDS, NKDS, NNDS, PPDS, and BBDS; SC5 hybrid in JTDS; while other hybrids, namely SC4, SC10, SC6, and SC11 didn't have locations that fall in the sector. In the rainy season, two PCs accounted for 68.34% of the total variation for grain yields (PC1 = 51.62% and PC2 = 16.72%) with one mega-environment identified namely JKRS, BBRS, KARS, PPRS, GJRS, and NNRS, with SC3 as the winning hybrid (Figure 4). Other vertex hybrids were SC5 in the JTRS environment, SC7 in the NKRS environment. While SC1 was a hybrid vertex in a sector that doesn't have an environment. Biplots based on the average data for two growing seasons at eight sites showed that the first two PCs accounted for 61.82% of the total variation (PC1 = 45.44% and PC = 16.38%) and the 16 test environments had five sectors with different winning hybrids (vertex) (Figure 5). The vertex hybrids were SC8, SC3, SC5, and SC11. Figure 5 represents the three mega-environments. The first mega-environment consisted of PPDS, BBDS, NNRS, PPRS, KADS, KARS, GJRS, JKDS, NNDS, GJDS, JKRS, NKDS, and BBRS with the winning hybrid SC3. The second mega environment includes JTRS and NNRS with SC8 as the vertex hybrid. JTDS was a single mega-environment with SC5 as the winning hybrid. SC11 was a vertex hybrid in the sector without environment, indicating that its yield performance was poor in all test environments.

The ideal hybrid was identified through the 'rank genotypes' pattern on the GGE biplot (Figure 6). This genotype has the stable and high yield performance in a variety of environments; that is, closer to the circle containing the arrow in the GGE biplot. To select the ideal hybrid, the average data for the two growing seasons was used. The most ideal hybrid was SC3 (Figure 6). SC4 and SC9 were identified to have the least effect of GEIs (Stable) and were close to the circle. Both hybrids also have above-average yields overall. SC11 and SC7 were identified as unfavorable hybrids due to their distance from the ideal point.

According to the 'ranking environment' pattern of the GGE biplot presented in Figure 7, the GJRS and KARS environments were the ideal environments for testing because they were at the ideal point (small arrow). These two locations were ideal for selecting superior hybrids because they have high discriminating power and representation. The JTRS environment was farthest from the ideal point, and close to the center of the biplot axis. This location provides small information about the maize hybrids tested, so they are not suitable for testing. Other environments were close to the ideal point but were outside the first circle, so it was useful for selecting hybrids in specific environments.

Discussions

The combined ANOVA showed highly significant differences ($P < 0.01$) on the main effects of growing season, location, genotype (hybrid), and their interactions (GEIs) (Table 1). This indicated that there were differences in genotypes and locations used. The highest difference was shown by the interaction effect of growing season and location (L × S) of 40.13%, while the main effect of genotype (hybrid) accounts for 14.59%, location was 12.55%, and their interactions (GEIs) was 12.69%. The effect of GEIs often occurred for maize yields in multi-environmental experiments [1]. The emergence of the effect of GEIs in multi-environment experiments makes the selection process complicated and less efficient [7,21,22]. The difference in yield performance of maize hybrids was probably due to differences in genetic background and various environmental conditions. The hybrids to be used are the result of directed crosses that have high genetic variation [23]. In addition, the emergence of the effect of GEIs causes researchers to carry out further analyzes on all hybrids tested using various stability measures. This was done to determine the hybrids with broad (stable) and specific adaptability.

The results of the stability measurement using a numerical approach (parametric in Table 3 and non-parametric in Table 4), showed that each hybrid had different potential in terms of stability. According to Ahmadi et al.[18], selection of stable genotypes with one stability measurement was considered less effective and accurate. The same thing was also expressed by several researchers who used various stability measurements to select stable and high-yielding genotypes, including barley [20], sweet potatoes [7,9], and soybeans [24]. Each stability measurement generally selects a different hybrid as the most stable. However, there were several measurements that select the same hybrid as the most stable, including CV_i, θ_i, $S^{(1)}$, $S^{(3)}$, $S^{(6)}$, $NP^{(3)}$, and $NP^{(4)}$ which consider SC3 as the most stable. In addition, there were also stability measurements that have the same output in terms of ranking the stability of all maize hybrids, namely W_i^2, σ^2_i, and $\theta_{(i)}$. In this case, measurements that have the same stability ranks can be used one of them to select stable genotypes [20].

The use of several yield stability measurements, can increase the accuracy of the maize hybrid selections. It was due to the difficulty of selecting hybrids with high yield performance and stability in a wide environment based on a single measurement [7,18]. Some researchers use the average sum rank (AR) to determine the stability of the hybrids tested, where the smallest AR value was the most stable [9,18,20]. In this study, SC9 was identified as having the smallest AR, followed by SC2 and SC3. The three hybrids have high average yields. To classify maize hybrids according to the yield ranks of each stability measurement, we used Hierarchical cluster analysis (HCA) (Fig. 1). The results of HCA visualization divided the tested hybrids into three main groups, namely 1. unstable high yield cluster containing SC8, SC10, SC4, SC1, and SC5 hybrids; 2. unstable low yield cluster containing SC7 and SC11 hybrids; 3. stable high yield cluster containing SC2, SC9, SC6, and SC3 hybrids (Fig. 1). The first group can be used as hybrids with high yield performance in specific environments. According to Ruswandi et al. [1], maize hybrids with high yield performance in specific environments, can be used as superior in certain areas. It was to increase the income/economics of farmers in certain environments by utilizing the potential of these crops. According to several researchers, high yields of agricultural products will have an impact on improving the community's economy [7]. The second group, less favored, because their performance was considered less good. While the third group was the most ideal group because of its yield performance and wide adaptability [18,24]. Thus, the third group was identified as more stable with high yield performance in a wide environment based on parametric and non-parametric stability measurements.

Graphical visualization based on PCA biplots was used to understand the relationship between the measurement and the stability concept (Fig. 2). PCA biplots were taken from the highest values of the first two PCs (Table 5). Based on PCA analysis, all stability measures were classified into three groups. The first group consisted of $NP^{(1)}$, b_i, W_i^2,S^2d_i, σ^2_i, and $\theta_{(i)}$ measurements; the second group consisted of KR, $S^{(1)}$, $S^{(2)}$, Di measurements; and the third group consisted of yields (Y) with $S^{(3)}$, $S^{(6)}$, $NP^{(2)}$, $NP^{(3)}$, $NP^{(4)}$, CV_i, and θ_i measurements. The first two groups represent the concept of static stability, so they can be used to select hybrids in less favorable environments [25]. The third group showed that the measures that were positively and significantly correlated based on the Spearman's rank correlation to maize hybrid yields, provided a measure of dynamic stability. They can be used to recommend ideal maize hybrids under favorable environmental conditions [20].

The GGE biplot can provide an overview of the differences between hybrids and environmental characteristics tested in multi-environment experiments. One display that shows the distribution pattern of hybrids and environments was “which won where/what”[26]. One of the characteristics of this pattern was the presence of polygons that indicate the location of the hybrid being tested. Hybrids that are at the top of the polygon (vertex) have the highest yields in the environment in that sector. Another important feature of this pattern was the grouping of environments, which suggests the possibility of different mega-environments [1,27,28]. Our results showed that, within each growing season, the sites fall into different groups and the pattern of site grouping varies throughout the seasons. The first two PCs explained 61.82–68.34% of the total variability due to the effects of hybrid (G), environment (location and growing season), and their interactions (Fig. 3, Fig. 4, and Fig. 5). The GGE biplot depicted the distribution of hybrids and environments in each season and the average of the two seasons showed two and three mega-environments. In the main mega-environment, SC3 was at the peak of the vertex in both the dry, rainy and average seasons. Meanwhile, mega-environment (single), showed the difference between vertex hybrids. SC9 hybrids were always close to the center of the axis in each growing season as well as the average. This showed that SC9 tends to be stable in various environmental conditions, in the other word that it has a small GEIs response. The two strategies for evaluating mega-environmental data (analysis of each growing season and its combination) showed that there was more than one mega-environment for maize breeding programs in various regions of Java Island (Indonesia) and divided them into certain sub-regions. However, based on the average data during two growing seasons, we found three mega-environments with different winning hybrids, indicated the presence of maize hybrids specific to the mega-environment and the presence of substantial GEIs. The ideal hybrid has high yield and stable in multi-environment testing[20]. SC3 followed by SC9 and SC4 were identified as ideal hybrids compared to others. This was also confirmed by numerical measurements (parametric and non-parametric), where HCA separated SC3 and SC 9 in the stable and high yield groups (Fig. 1). Based on these results, both measurement steps (numerical and graphical) produced the same pattern in selected stable and high yielding maize hybrids. This was similar to previous studies which reported that stability measurements based on parametric, non-parametric, and GGE biplots resulted in the same pattern in stable and high yielding selection, including sweet potato [28] and safflower [29]. In environmental testing, discriminative and representative were two key measures. Where the ideal test environment should best differentiate the hybrids tested and be representative of all environments [26,30]. In this study, the GGE biplot display (ranking environments) revealed that the GJRS and KARS environments have high discriminative power and were at the ideal point (small arrow) (Fig. 7). While the JTRS environment was farthest from the ideal point, and close to the center point of the biplot axis. This location provided small information about the maize hybrids tested, so they are not suitable for testing.

Conclusions

The results of the analysis showed that the main effects of growing season, location, hybrid (G), and their interactions gave a significant influence (p<0.01) on the variation of maize hybrid yields in Java Island, Indonesia. Stability measurements $NP^{(1)}$, bi, Wi^2, S^2di, $\theta_{(i)}$, σ^2_i, KR, $S^{(1)}$, $S^{(2)}$, and Di were included in the concept of static stability, while $S^{(3)}$, $S^{(6)}$, $NP^{(2)}$, $NP^{(3)}$, $NP^{(4)}$, CVi, and $\theta_{(i)}$ were included in the concept of dynamic stability. SC3 and SC9 were identified as the most stable and high yielding yields, so they can be recommended for maize development programs in Indonesia. GJRS and KARS were the most representativeness environments and have high discriminatory power, so they can be used as favorable environments for selecting the ideal maize hybrid.

Declarations

Ethical Approval: All experiments on maize hybrid plants were carried out according to the guidelines of Ministry of Agriculture, Republic of Indonesia. The plant material used in the study is a cultivated plant, not-lethal collecting, and not threatened species. In addition, the material used was maize hybrids derived from cross-bred by the plant breeding laboratory of Universitas Padjadjaran (UNPAD) as an effort to increase crop production to meet domestic needs.

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Conflicts of Interest: The author(s) declare no competing interest.

Data Availability: The data used to support the findings of this study are included within the article.

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Tables

Due to technical limitations, table 1-8 is only available as a download in the Supplemental Files section.

Figures

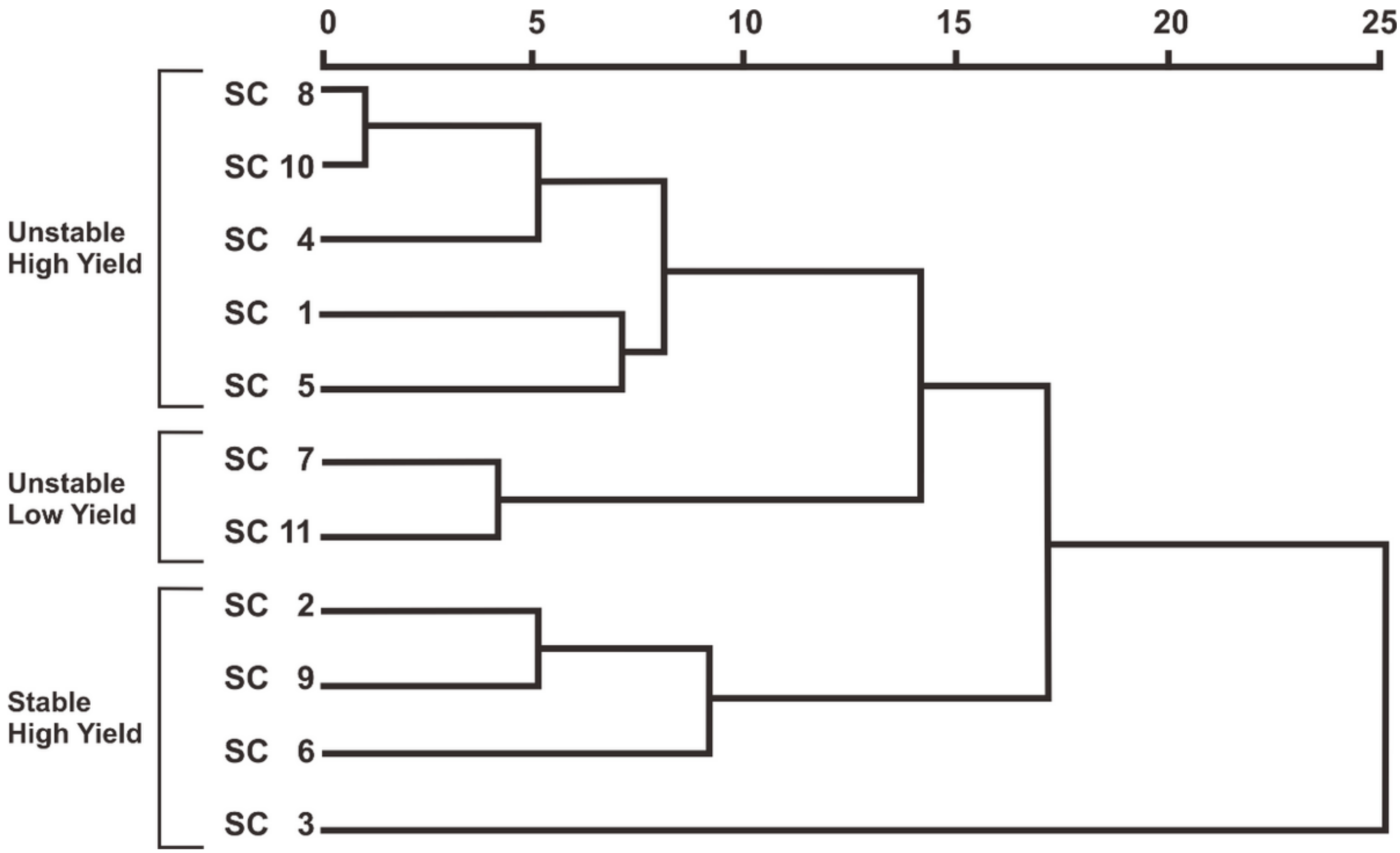

Figure 1

Maize hybrids were grouped based on parametric and non-parametric stability ranks at eight locations for two growing seasons.

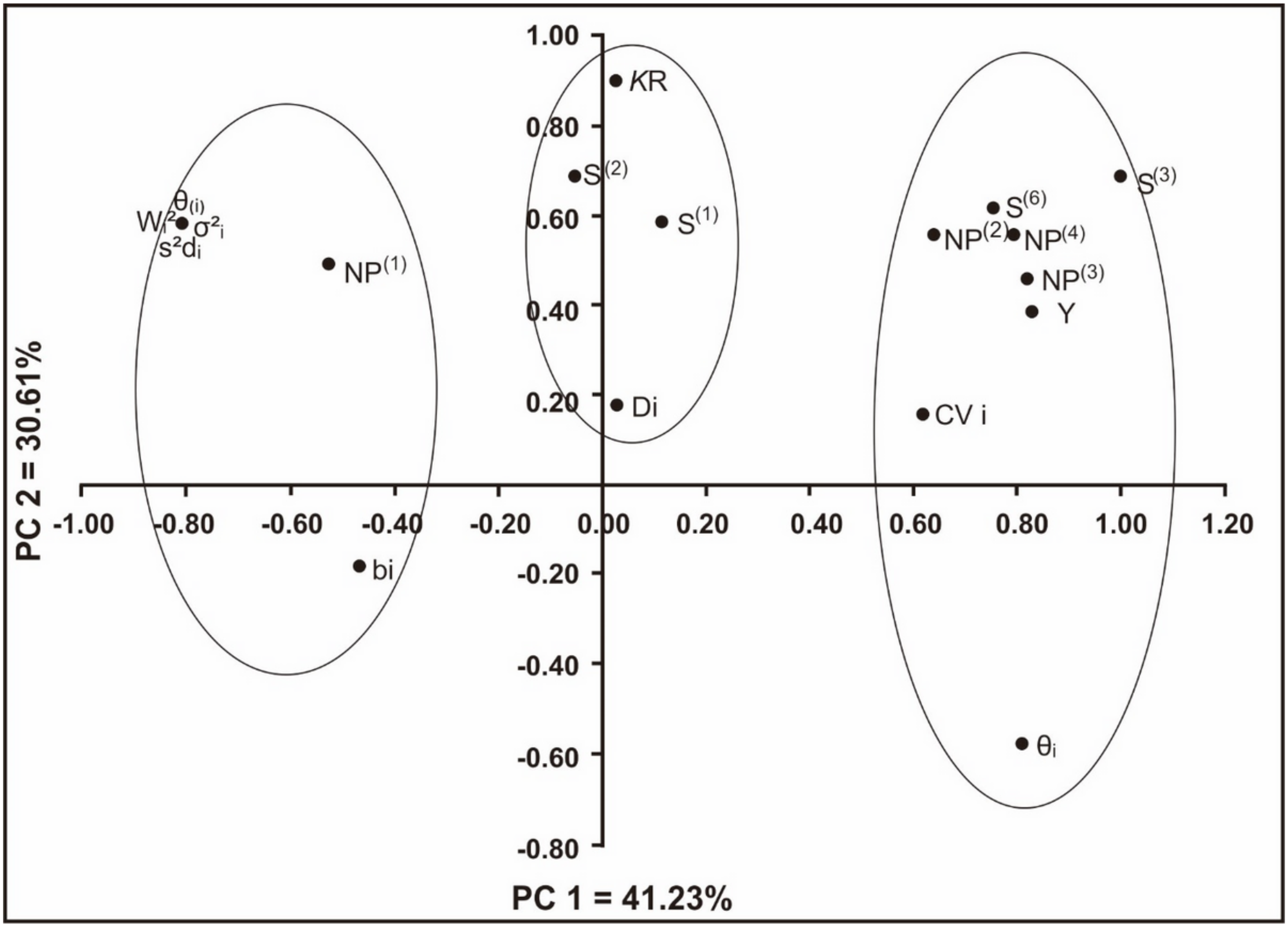

Figure 2

Classification of stability measurements based on PCA

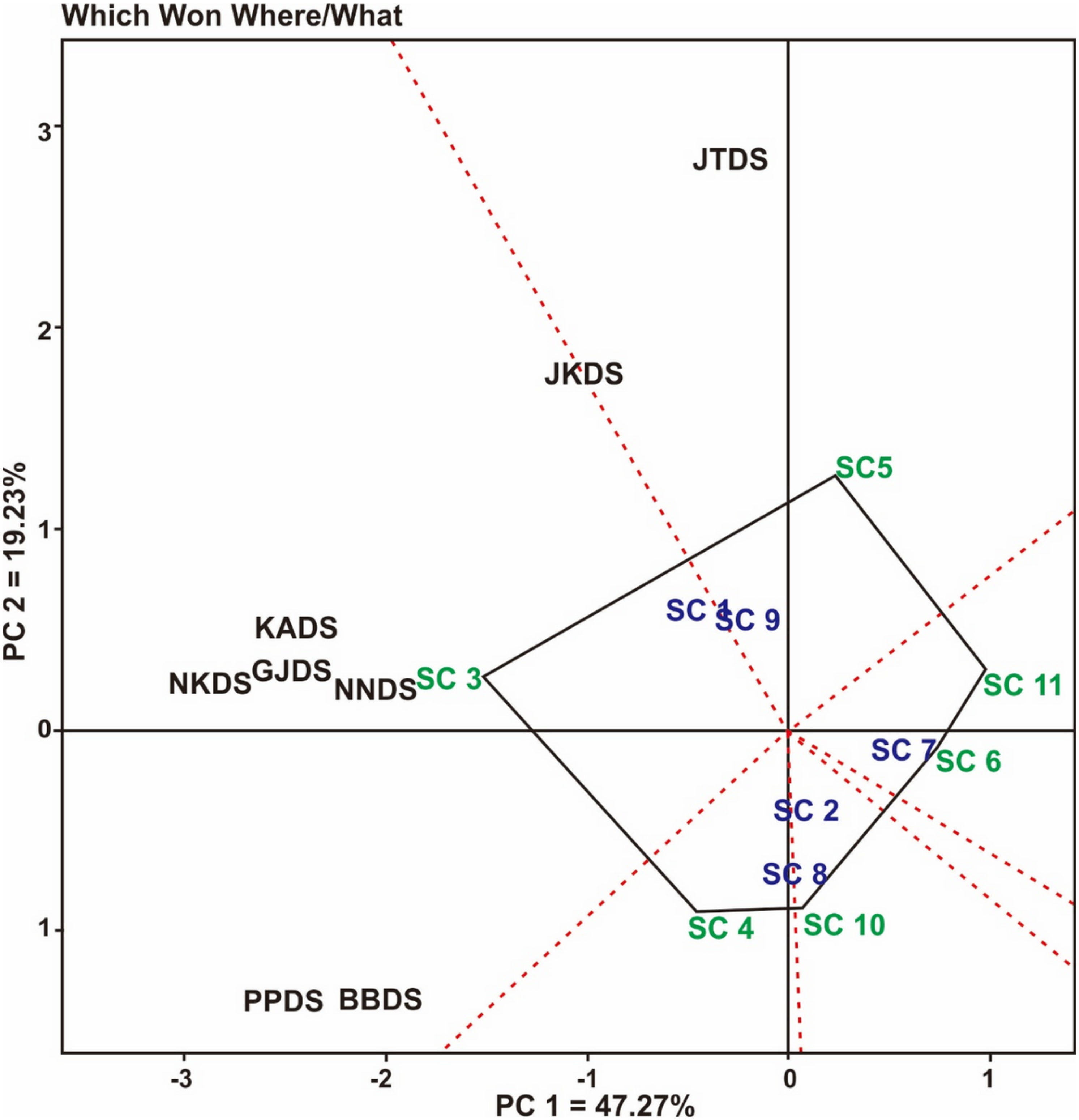

Figure 3

Mega-environment and vertex hybrids based on dry season data. See Table 1 and Table 2 for legends

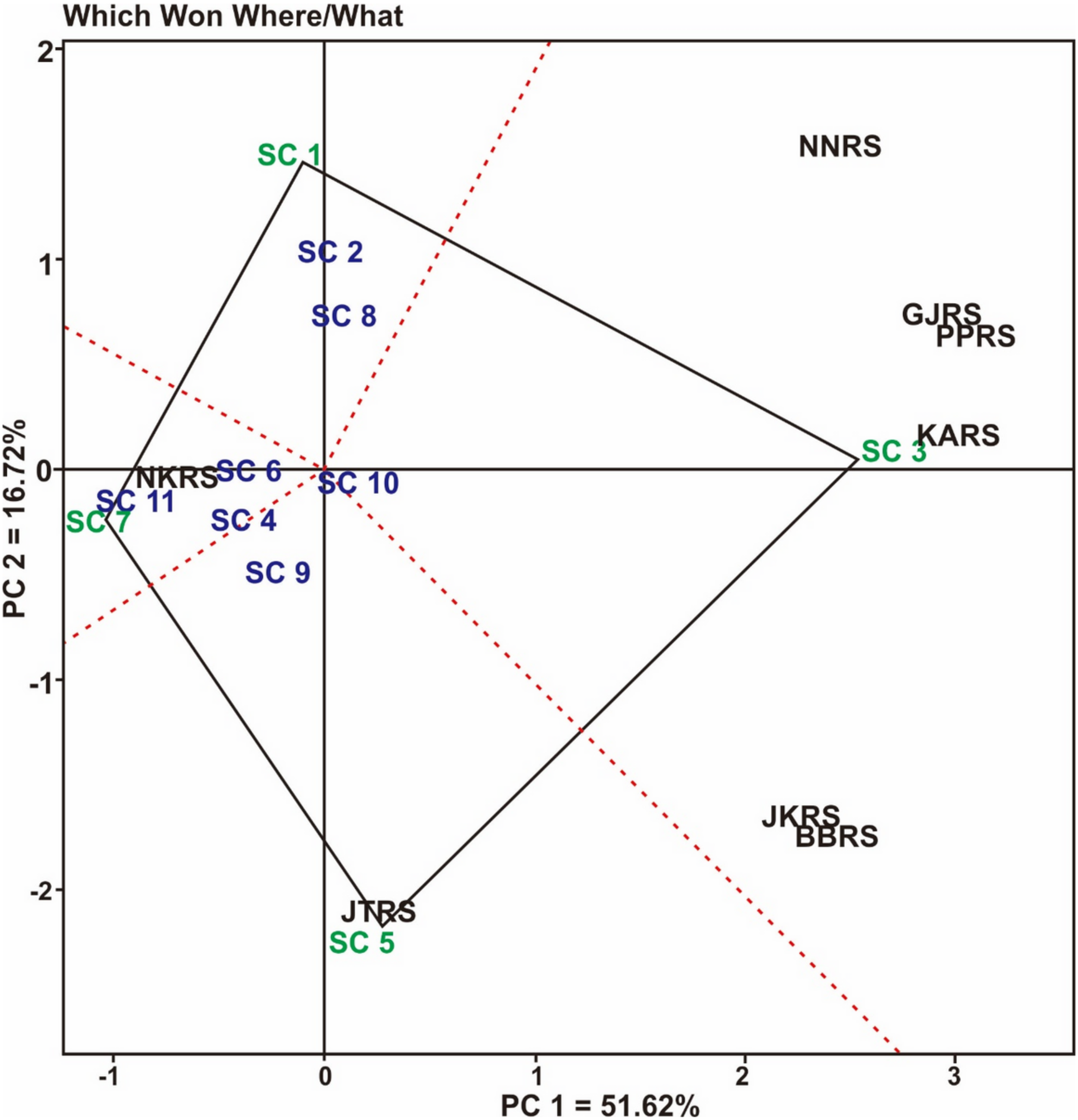

Figure 4

Mega-environment and vertex hybrids based on rainy season data. See Table 1 and Table 2 for legends

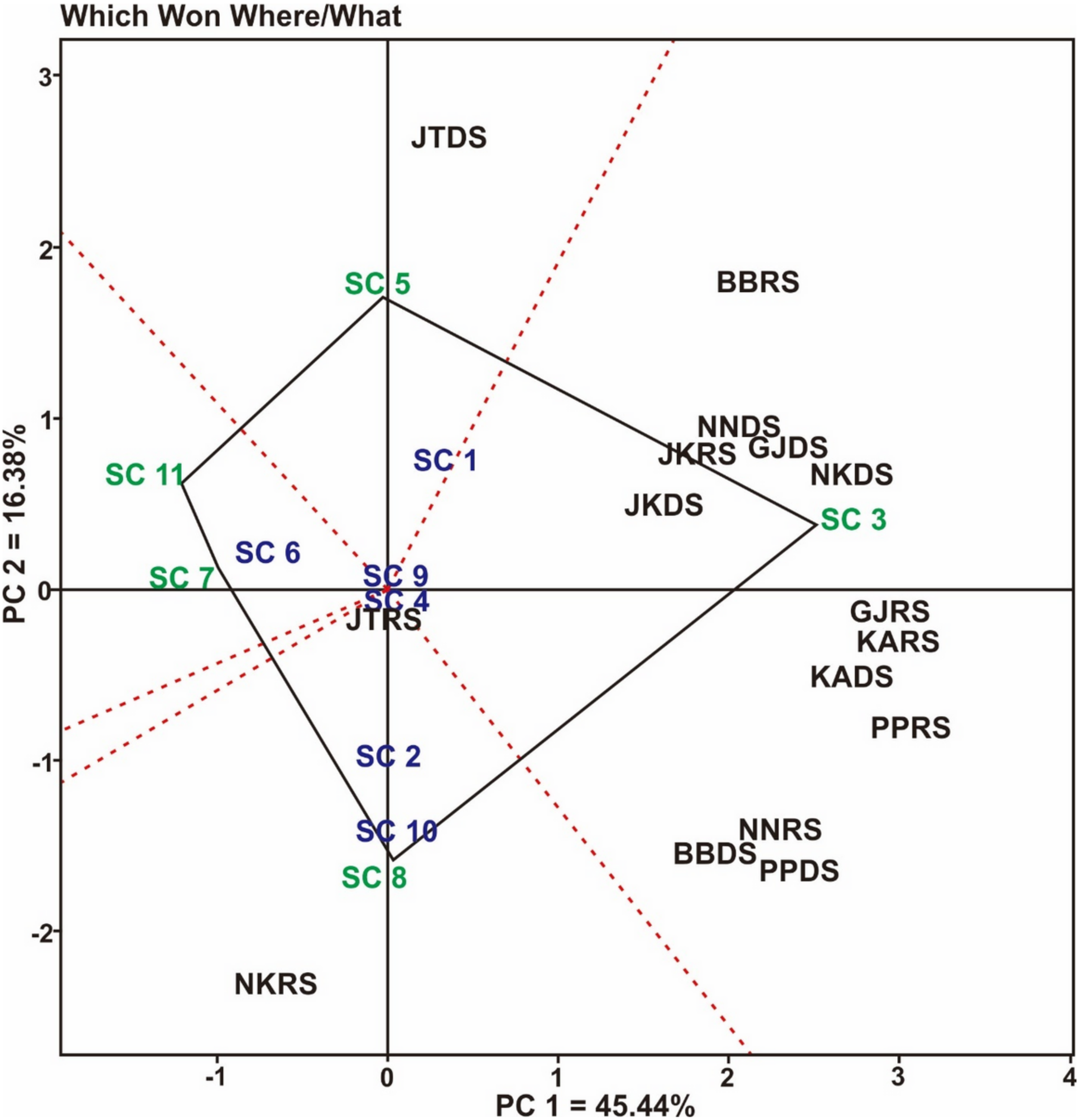

Figure 5

Mega-environment and vertex hybrids based on the averaged 2-growing season data. See Table 1 and Table 2 for legends.

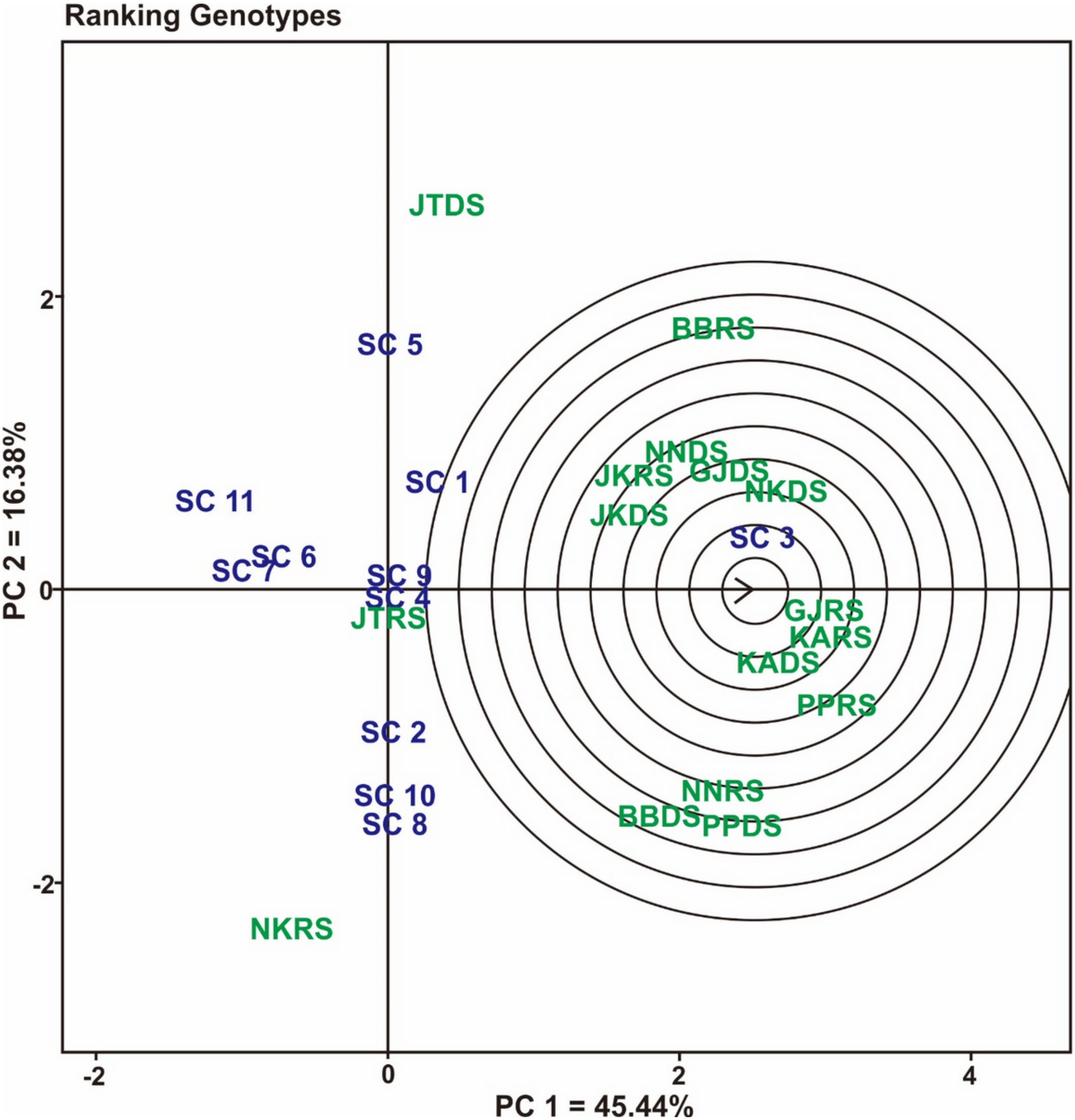

Figure 6

comparison of maize against the ‘ideal’ hybrids for grain yield across eight test locations in Java island, Indonesia during 2-growing seasons. See Table 1 and Table 2 for legends.

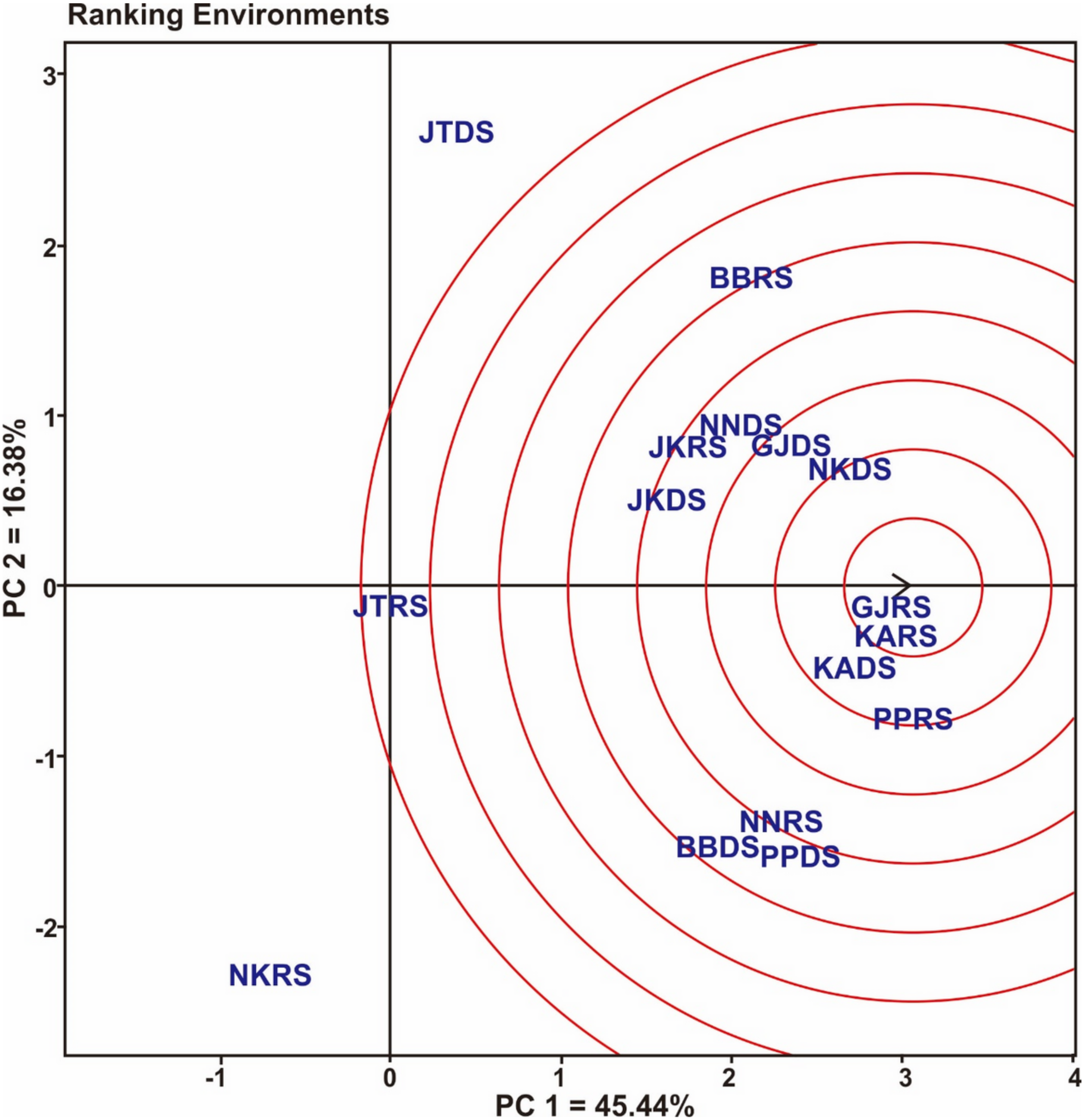

Figure 7

The ‘Discriminating and representativeness’ view of the 16 environments using GGE biplot. See Table 2 for legends.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Tables.pdf