Mega-Environment Analysis and Identify Stable and High-Yielding of New Promising Black Soybean Lines in Indonesia

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Abstract

Stable and high-yielding are the major goals of black soybean breeding. Testing new lines in a mega-environment is one of the development processes in black soybean breeding. The aims of the research were (i) to identify the effects of genotype, environment, and GEIs on the grain yield of soybean lines in Java Island; (ii) to select stable and high yielding soybean lines; and (iii) to determine the discriminative environments, and (iv) to determine the concept of stability measurements on black soybean grain yields. Field trials of 10 new F8 promising lines and three check varieties were conducted under eight different environments during four years (2016–2019). The measurement results showed that the grain yield was influenced by genotype (8.35%), environment (59.49%), and GEIs (32.16%). Grain yield stability measurements showed that the four newly lines was identified had high yields and stable in eight environments, they were A-5A-PSJ (S2), DB-96-CTY (S5), UP 161 (S6), and UP 162 (S7). The Ngawi (2017) followed by Bogor (2019) and Banyuwangi (2016) has the strongest interactive capabilities, and was suitable for used as a trial environments. Grain yield (Y) was identified as having a positive and significant correlation (p < 0.05) with S3, S6, NP2, NP3, NP4, KR, and YSI stability measurements, which indicated that they were included in the concept of dynamic stability measurement.

Introduction

Black Soybeans contain many nutrients that are beneficial for humans. The current research of black soybean leading to the results of secondary metabolites that are beneficial to health. There were many secondary metabolites of black soybeans that are beneficial to humans, one of which is isoflavones. Isoflavones are a group of flavonoid compounds that produce natural antioxidants 1. The benefits of isoflavones for humans include preventing cancer, heart attack, and climacteric syndrome 2,3. Isoflavones in black soybeans were found in all plant organs, especially soybean seeds. Sumardi et al. 4 reported that the largest types of isoflavones contained in black soybean seeds were daedzein and genistein. The important role of black soybeans for food and human health, makes this commodity increasingly needed by the community so that its demand was predicted to increase.

In Indonesia, black soybeans were still needed as raw materials for production in soy sauce industries. The advantage as a raw material for soy sauce was to improve the quality of the color to dark chocolate. Soy sauce made from black soybeans “Merapi” has a protein content of 3.20%, higher than the soy sauce from the yellow soybean “Argomulyo” (2.37%) 5. The large role of black soybeans for functional foods, makes the demand for black soybeans increase. Triyanti 6 reported that soybean production in 2020 had increased to 632,333 tons from 2019 which produced 424,190 tons. However, this amount was still not able to meet the higher demand for black soybeans, so it was predicted that the import value of s black oybeans to meet domestic needs was still high.

One of the efforts that can be done is by assembling new superior black soybean that have high grain yields. The stages that must be passed in the assembly of promising lines are testing in a variety of environments (multilocation trial). Multi-location trials was carried out to obtain information on stable and adaptive lines in all environments as well as specific adapted lines with high yields. The more environments used for testing (mega-environment), the higher the accuracy of stable lines 7. According to Srivastava et al. 8, mega-environment analysis using the GGE biplot provides information on suitable sites for extensive adaptation and suitable sites for specific adaptation testing. Silva et al. 9 reported that mega-environment trials could lead to complex GEIs and obtained information about the relationship between trial environments. Information obtained from mega-environment trials was very helpful for plant breeders in manages of GEIs and extracting them into the same agro-climatic concept 10. According to Zdierski et al. 11, mega-environment trial provides information on specific adapted lines based on regional targets and regional climate. In addition, based on these environment groupings, lines that show high yield stability and high yielding in suitable locations for recommended lines. Based on this description, the objectives of this study were (i) to identify the effects of genotype, environment, and GEIs on the grain yield of soybean lines in Java Island; (ii) to select stable and high yielding soybean lines; and (iii) to determine the discriminative environments, and (iv) to determine the concept of stability measurements on black soybean grain yields. The results information was useful in the development of soybean lines in the future.

Result

Combined Analysis of Variance (ANOVA) to identify GEIs

AMMI ANOVA (Table 1) revealed that the effect of genotype, environment, and their interactions (GEIs) had a significant effect (P < 0.05) on soybean grain yield variations. The main effect of genotype accounted for 8.35% of the total variation, while environment and GEIs accounted for 59.49% and 32.16%, respectively. These results indicated that grain yields were significantly affected by environmental changes, followed by effects of GEIs and genotypes (Table 1). Highly significant environmental effects and high variance components can be attributed to large differences between test environments such as elevation, and differences in the amount and distribution of annual rainfall (Table 2). The GEIs were further divided into seven IPCAs, of which the first two IPCAs showed significant contributions. IPCA1 contributed 42.66% to the number of squared GEIs. The first two IPCAs accounted for 69.30% of the total variation in GEIs indicating the accuracy of the data. The magnitude of the GEIs effects was also be seen in the box plot (Figure 1) and the GEIs heatmap (Figure 2). In Figure 1 the distribution of the average grain yield in each environment showed high variation. The GEIs heatmap (Figure 2) showed the relationship between each environment and the average yield. In Figure 2, the environment was divided into three main clusters, namely environmental groups that have high average grain yields (E4 and E5), low grain yield (E2, E6, and E7), and medium grain yield (E1, E3, and E8). This data showed that the influence of the environment was very strong on soybean grain yields.

Parametric and non-parametric stability measurements on soybean grain yields

The stability of soybean grain yields in multi-environmental trials based on parametric and non-parametric measurements was presented in Table 3. Linear regression measurements on environmental indexed showed that grain yields of the two stability parameters bi and S2di were inconsistent in assessing the all lines showed a regression coefficient value (bi) which was not significantly different from one
respectively. Vertex line GH Detam 5 (S13), without the environment in its sector, so it’s not a line that has a high average grain yield in all environment.

The winner. The second mega-environment (ME-II) consisted of Banyuwangi (2016) and Probolinggo (2018) with the Detam 3 (S12) line as the winner. Bantul

yields (Figure 7). Biplots based on average data during four years showed that the eight test environments had ve sectors with different winning lines

2016–2019, PC1 explained 46.28% of the total variation and PC2 explained 23.56% of the total variation, accounting for 67.84% of the total variation for grain

The genetic correlations between the eight environments was presented in Table 5 and reected in the GGE biplot (Figure 7). In the GGE biplot analysis in

Mega-environments analysis of 13 soybean lines in eight environments

Prodolingo (2018) with the Detam 3 (S12) line as the winner. The second mega-environment (ME-I) consisted of Ngawi (2016) and Bogor (2019), Ngawi (2017), and Malang (2018) environment has the weakest interactive. The lines that clustered close to the biplot axis had stable yields across the environment. Thus, the A-

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Discussion

The development of stable and high yielding black soybean lines is one of the goals of the current breeding program. Effects of GEIs are frequent for many quantitative traits including grain yield, reproductive fitness, harvest time, and biotic and abiotic resistance. The emergence of GEIs in multi-environment experiments makes it difficult to select the superior line. In this study, the combined ANOVA showed that the effects of environment (E) and GEIs explained 59.49 and 32.16% of the total variability of the grain yield, respectively (Table 1). The box plot (Fig. 1) and heatmap GEIs (Fig. 2) also showed that the tested environments and lines had high grain yield variations. Since combined ANOVA cannot explain the effect of GEIs, other statistical models such as AMMI and GGE are more useful. Therefore, parametric and non-parametric measurements were used to estimate the adaptability of the lines to a wide range of environments. The magnitude of the environmental and GEIs effects showed that the test environment had a significant effect on grain yields. Differences in rainfall, humidity, and light in each environment during the experiment had a significant effect on soybean grain yields. In this study, the Ngawi (2017) had the highest average grain yield (2.54 t/ha) compared to other environments. The average daily rainfall during the experiment in Ngawi (2017) was 15.31 mm (Table 2). According to Mandic et al., rainfall was related to soybean grain yields. In other studies, rainfall also affects in sweet potato yields. In addition, the humidity during the experiment also showed suitable conditions for growth and development of soybean.

Stability and adaptability analyzes were used when the results of the combined ANOVA indicated the presence of GEIs. In this case, we used various stability measurements, namely parametric, non-parametric, AMMI, and GGE biplot. The use of various measurements aims to increase accuracy in selecting stable and high yielding lines tested. The parametric and non-parametric measurements presented in Table 4, showed that each measurement selects a different stable line. This is because each measurement has different assumptions in terms of calculating stability and adaptability. However, there were several measurements showing uniform output, namely W12, σ12, and 912. In other studies, it was also reported that there were parametric measurements that had similar results, including Vaezi et al., on barley in Iran. According to Karuniawan et al., if there were stability measurements that have similar outputs, one of them can be chosen to estimate the stability of the yield. Ruswandi et al. showed different things, all parametric and non-parametric measurements showed differences in selecting stable maize. This difference in output indicates that another approach was needed to classify the stable lines based on parametric and non-parametric measurements. The approach commonly used in cases like this was Hierarchical Cluster Analysis (HCA). Based on the HCA results, the tested lines were divided into three main groups, namely unstable low yield, unstable high yield, and stable high yield groups (Fig. 3). Lines belonging to unstable low yield group include A-4A-PSJ (S1), UP 165 (S10), A-8A-PSJ (S4), and GH Detam 5 (S13). This first group was less favored because of low grain yields, which will result in low economic income. The second group, namely unstable high yield, consists of the Detam 1 (S11), Detam 3 (S12), A-7A-PSJ (S3), and UP 164 (S9) lines. The second group can be used for specific adapt. Meanwhile, the third group, namely stable high yields, consists of DB-96-CTY (SS), UP 162 (S7), UP 161 (S6), UP 163 (S8), and A-5A-PSJ (S2). The third group was the expected ideal group. According to, a stable and high yielding lines is one of the targets for soybean breeding. In addition, lines with high and stable yields are expected to increase farmers’ income. Thus, this group was strategically developed for a further sustainable soybean breeding program.

To classify parametric and non-parametric stability measurements, the principal component analysis (PCA) was used. The results of PCA (Fig. 4) and correlation analysis (Table 4) showed that the grain yield (Y) in the same group with NP1, NP2, NP3, S1, S2, S3, S4, S5, and YSI. This group belongs to the concept of dynamic stability. Another group that correlates with each other were S1 with S2, bi with NP1, S2 with ASV, 612, σ12, and W12. While Cvi and 81 were not grouped with other measurements. These groups were included in the concept of static stability. Thus, dynamic stability groups can be used to select lines in favorable environments. While the static stability group can be used to select lines in an unfavorable environment.

AMMI biplots showed that the first two principal components (IPCA1 and IPCA2), explained 69.2% of the total variation of GEIs (Fig. 5). In Fig. 5, the lines A-4A-PSJ (S1), A-5A-PSJ (S2), A-7A-PSJ (S3), DB-96-CTY (SS), and UP 162 (S7) were closest to the biplot axis point. According to several researchers, the lines that were close to the biplot axis were the most stable. The Ngawi (2017) environment has the longest vector length followed by Bogor (2019) and Banyuwangi (2016), while Malang (2018) has the shortest vector. According to, the environmental vector length from the center of the biplot was proportional to the number of GEIs. This shows that the Ngawi (2017), Bogor (2019), and Banyuwangi (2016) have a strong interaction, while the Malang (2018) environment has a weak interaction.

In the AMMI biplot PC1 vs Yield (Fig. 6), the first IPCA biplot (IPCA1) was plotted against the line and environmental mean. The environments and lines tested on the left side of the vertical line had grain yields below the overall average grain yield, while those on the right had above the overall average grain yield. Ngawi (2017) environment was classified as had the highest average yield compared to other environments, and the lines that close to this environment were DB-96-CTY (SS) and UP 162 (S7). The Malang (2018) environment was identified as had the lowest average yield and a small positive IPCA value close to zero while Banyuwangi (2017) has a small negative IPCA value which was close to zero with an average grain yield of less than the overall average grain yield. These two environments were not suitable for testing and development of soybeans. Lines that were close to the horizontal line have stable grain yields. Overall, of the 13 lines tested, six lines (46%) produced grain yields above the overall average grain yield, namely A-5A-PSJ (S2), A-7A-PSJ (S3), DB-96-CTY (SS), UP 162 (S7), UP 164 (S9), and Detam 3 (S12), with three lines that were close to the horizontal line (stable), namely A-5A-PSJ (S2), DB-96-CTY (SS), and UP 162 (S7). While the other seven lines (54%) had grain yields below the overall average grain yield. According to several researchers, the lines that were on the right side and close to the horizontal line were potential lines and can provide economic income. The mega-environment trials used the GGE biplot “which won where” (Fig. 7). The results of the GGE biplot analysis provided an opportunity to detect differences between environments with different characteristics related to the performance of the tested lines in these environments. The line at the top of the sector (vertex) has the highest yield for the environment in that sector. One of the important features of this biplot was the clustering of environments, which suggests the possibility of different mega-environments. Our results showed that during 2016–2019, the environments fell into different clusters with varied environmental cluster patterns. The first two PCs accounted for 67.84% of the total variability attributable to the effects of genotype (G),
environment (E), and their interactions (GEIs) over 4 years (Fig. 7). Based on 4 years of average data, we found four mega-environments with different vertex lines. This suggests a specific adaptation of the line to the mega-environment and positive exploitation of GEIs. Our findings revealed that some of the new lines were better adapted to different environments on the Java island (stable) than other lines and check varieties. Based on our results, both numerical (parametric and non-parametric) and graphical (AMMI and GGE biplot) measurements resulted the same pattern for the identification of stable soybean lines. For example, parametric and non-parametric stability measurements identified the DB-96-CTY (S5), UP 162(S7), UP 161 (S6), and A-5A-PSJ (S2) lines as the most stable and high yielding than others. The AMMI biplot identified A-5A-PSJ (S2), DB-96-CTY (S5), UP 161 (S6), and UP 162 (S7) lines, as the most stable and high yielding. The GGE biplot identified A-5A-PSJ (S2), DB-96-CTY (S5), UP 161 (S6), UP 162 (S7), and Detam 1(S11) as the most ideal lines. Similarly, Karuniawan et al. used a numerical measurements, AMMI, and GGE biplot to select stable sweet potato in West Java, Indonesia. Several other studies also reported the relative contribution of these various measurements to identify the ideal line, including Vaezi et al. on barley, Oyekunle et al. on maize, Jamshidmoghaddam & Pourdad on safflower. From our test results, there were four new soybean lines that were identified as stable and high yielding by various stability measurements, namely A-5A-PSJ (S2), DB-96-CTY (S5), UP 161 (S6), and UP 162 (S7). They were can be further proposed as candidates for superior black soybean lines in Indonesia.

Conclusion

The effects of genotype (G), environment (E), and their interactions (GEIs) have an influence on black soybean grain yield variations with contributions of 8.35%, 59.49%, and 32.16% of the total variation, respectively. Four new black soybean lines were identified as having high and stable grain yields in diverse environments on the Java island, namely A-5A-PSJ (S2), DB-96-CTY (S5), UP 161 (S6), and UP 162 (S7). The Ngawi (2017) followed by Bogor (2019) and Banyuwangi (2016) environments has the strongest interactive. The stability measurements NP(2), NP(3), NP(4), S(6), S(6), KR, and YSI were included in the concept of dynamic stability that can select the best lines in a favorable environment.

Materials And Methods

Plant Material and Field Experiments

Planting materials used include 10 new promising F8 black soybean lines, namely, A-4A-PSJ (S1), A-5A-PSJ (S2), A-7A-PSJ (S3), A-8A-PSJ (S4), DB-96-CTY (S5), UP 161 (S6), UP 162 (S7), UP 163 (S8), UP 164 (S9), and UP 165 (S10), as well as three check varieties as control, namely Detam 1 (S11), Detam 3 (S12), and GH Detam 5 (S13). The experiment was carried out in eight environments in Java Island, Indonesia during four years (2016–2019) including Ngawi (2016), Banyuwangi (2016), Banyuwangi (2017), Ngawi (2017), Probolinggo (2018), Malang (2018), Bantul (2019), and Bogor (2019). The climate condition of eight environments was presented in Table 2. The field experiment used a randomized completed block design which was repeated four times. Each line was planted on a plot 3 x 5 m² with a spacing of 20 cm x 30 cm.

Grain yield measures

A total of 13 black soybean lines were observed for their grain yield following the standard Descriptor for Soyabean. Grain yield was harvested when the pods are brown. The grain yield data per plot was converted to ton/ha.

Statistical Analysis

The combined ANOVA statistical model to estimate GEIs follows the equation

\[ Y_{opqr} = \mu + G_o + E_p + G_E_{op} + R_{q(p)} + B_{r(q)} + \varepsilon_{opqr} \]

where \( Y_{opqr} \) is the value of line \( o \) in plot \( r \), and the value in location \( p \) of each replication \( q \); \( \mu \) is the grand mean; \( G_o \) is the effect of line \( o \); \( E_p \) is the effect of the environment \( p \); \( G_E_{op} \) 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 \( \varepsilon_{opqr} \) is the error effects from line \( o \) in plot \( r \) and repeat \( q \) of location \( p \), respectively. To calculate the combined ANOVA used Genstat 12th.

Grain yield stability was estimated using parametric and non-parametric measurements (Table 6). To calculate grain yield stability based on parametric and non-parametric measurements used STABILITYSOFT.

Identification of stable lines among the selected genotypes was conducted using AMMI following the study of:

\[ Y_{ij} = \mu + G_i + E_j + \sum_{k=1}^{n} (a_k q_k y_{ij}) + \lambda_{ij} + \rho_{ij} \]

where: \( Y_{ij} \) is the yield in location \( j \) from line \( i \) of replication \( k \), \( \mu \) is the average of grand yield, \( G_i \) is the influence of line \( i \), \( E_j \) is the influence of the location \( j \), \( \lambda_k \) is the value of primer component \( k \), \( a_k \) and \( y_{ij} \) were the vector score for the line \( i \) and location \( j \) to component \( k \), \( \rho_{ij} \) is a mistake from line \( i \) and location \( j \).

While ASV was estimated following the study of:

\[ ASV = \frac{\text{SS IPCA}^2 + \text{SS IPCA}^2}{\text{SS IPCA}^2 + \text{SS IPCA}^2} \]
ss IPCA1, ss IPCA2 were the sum of square in IPCA 1 and 2, which shows the score of the main component because of the high contribution in genotype by location interactions. IPCA1 and IPCA2 were the first and second from IPCA scores for each genotype from the AMMI analysis.

The model for GGE biplot following with the formula:

\[ Y_{mn} - \mu_m = \beta_n + \sum_{k=1}^{r} \lambda_k \sigma_{mk} Y_{no} + \varepsilon_{mn} \]

where \( Y_{mn} \), \( \mu_m \), \( \beta_n \), \( \lambda_k \), \( \sigma_{mk} \), \( Y_{no} \) and \( \varepsilon_{mn} \) 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. Visualization of AMMI and GGE biplots using R program.

Declarations

Ethical Approval: All experiments on black soybean plants were carried out according to the guidelines of ILETRI – Indonesian Legumes and Tuber Crops Research Institute. The plant material used in the study is a cultivated plant, not-lethal collecting, and not threatened species. In addition, the material used was black soybeans resulted cross-bred from the plant breeding laboratory of Universitas Padjadjaran (UNPAD) and ILETRI as an effort to increase crop production to meet domestic needs. The use of this plant materials has also complied with the provisions of Law Number 11 of 2013 in Indonesia in accordance with the Ratication of the Nagoya Protocol on access to genetic resources, fair and balanced profit sharing arising from its use.

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Authors Contribution

G.W.A.S., P.H.P., A.K., conceived, planned, and designed the study; G.W.A.S., P.H.P., and A.A.W. conducted experiments and collected the data. H.M. and A.K., analyzed the data and wrote the manuscript. H.M. prepared Figure 1-7 and Table 1-6. G.W.A.S., P.H.P., and A.A.W. critically edited the manuscript. All authors reviewed the manuscript.

Competing Interests Statement

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**

Table 1. Combined ANOVA and AMMI analysis of new promising soybean lines in eight environments
| Source      | df  | SS     | MS   | F      | % Treatment | % GEIs |
|-------------|-----|--------|------|--------|-------------|--------|
| Total       | 415 | 108.39 | 0.26 | *      | *           |        |
| Treatments  | 103 | 50.66  | 0.49 | 2.97   | **          |        |
| Genotypes   | 12  | 4.23   | 0.35 | 2.13   | * 8.35      |        |
| Environments| 7   | 30.13  | 4.31 | 10.21  | ** 59.49    |        |
| Block       | 24  | 10.12  | 0.42 | 2.55   | **          |        |
| Interactions| 84  | 16.29  | 0.19 | 1.17   | * 32.16     |        |
| IPCA1       | 18  | 6.95   | 0.39 | 2.33   | ** 42.66    |        |
| IPCA2       | 16  | 4.34   | 0.27 | 1.64   | * 26.64     |        |
| IPCA3       | 14  | 2.93   | 0.21 | 1.27   | 17.99       |        |
| IPCA4       | 12  | 1.32   | 0.11 | 0.66   | 8.10        |        |
| IPCA5       | 10  | 0.46   | 0.05 | 0.28   | 2.82        |        |
| IPCA6       | 8   | 0.23   | 0.03 | 0.17   | 1.41        |        |
| IPCA7       | 6   | 0.06   | 0.01 | 0.06   | 0.37        |        |
| Error       | 288 | 47.62  | 0.17 |        |             |        |
| Minimum (ton/ha) | 0.72 |        |      |        |             |        |
| Mean (ton/ha)    | 2.11 |        |      |        |             |        |
| Maximum (ton/ha) | 3.68 |        |      |        |             |        |
| SD           | 0.51|        |      |        |             |        |
| CV (%)       | 19.25|        |      |        |             |        |

df = degree freedom; SS = sum of square; MS = mean of square; GEIs = genotype by environment interactions; *p<0.05; **p<0.01; SD = Standard of deviation

Table 2. Climate conditions in the eight environments

| Locations | Ngawi (2016) | Banyuwangi (2016) | Banyuwangi (2017) | Ngawi (2017) | Probolinggo (2018) | Malang (2018) | Bantul (2019) | Bogor (2019) |
|-----------|--------------|-------------------|-------------------|--------------|--------------------|---------------|---------------|--------------|
| tavg (°C) | 27.95        | 28.28             | 27.53             | 26.10        | 26.58              | 23.24         | 26.26         | 21.38        |
| RH (%)    | 67.50        | 92.00             | 79.00             | 85.00        | 77.60              | 71.42         | 78.75         | 90.13        |
| DR (mm)   | 18.18        | 31.96             | 33.04             | 15.31        | 17.50              | 4.65          | 2.44          | 14.67        |
| ss (hour/day) | 6.37   | 7.91              | 7.54              | 7.11         | 4.71               | 7.89          | 7.63          | 2.19         |
| Altitude (masl) | 55.00 | 168.00           | 168.00           | 55.00        | 85.00              | 335.00        | 45.00         | 120.00       |

tavg = temperature average (°C); RH = humidity (%); DR = daily rainfall (mm); ss = solar radiation (hour/day); masl = meters above sea level

Table 3. The result of stability analysis on soybean lines based on parametric and non-parametric measurements.
| Genotypes  | Y   | s²d | b | Wi² | σ² | CV | θ | θi | ASV | YSI | S(²) | S(³) | S(IV) | NP(²) | NP(³) | NP(IV) |
|------------|-----|-----|---|-----|----|----|---|----|-----|-----|------|------|--------|-------|-------|--------|
| A-4A-PSJ   | 2.01| 0.03| 0.94| 0.23| 0.03| 40.63| 0.04| 0.04| 0.27 | 15.00| 4.67 | 17.03 | 29.90 | 6.73  | 3.56 | 1.19 | 0.81  |
| A-5A-PSJ   | 2.15| 0.01| 1.05| 0.12| 0.01| 41.83| 0.05| 0.03| 0.25 | 9.00 | 4.33 | 12.86 | 13.04 | 3.44  | 2.56 | 0.30 | 0.38  |
| A-7A-PSJ   | 2.28| 0.08| 1.09| 0.62| 0.09| 42.59| 0.04| 0.07| 0.83 | 14.00| 4.22 | 13.36 | 12.03 | 3.03  | 4.11 | 0.34 | 0.51  |
| A-8A-PSJ   | 1.98| 0.05| 0.89| 0.38| 0.05| 39.64| 0.04| 0.05| 0.41 | 20.00| 3.72 | 9.75  | 14.63 | 4.25  | 3.33 | 0.78 | 0.79  |
| DB-96-CTY  | 2.20| 0.03| 1.07| 0.20| 0.03| 41.85| 0.05| 0.04| 0.30 | 8.00 | 3.56 | 9.00  | 8.00  | 2.22  | 3.11 | 0.31 | 0.42  |
| UP 161     | 2.08| 0.03| 1.00| 0.18| 0.02| 41.39| 0.05| 0.04| 0.17 | 10.00| 3.94 | 10.75 | 12.90 | 3.50  | 2.11 | 0.38 | 0.43  |
| UP 162     | 2.19| 0.03| 1.03| 0.22| 0.03| 40.73| 0.04| 0.04| 0.22 | 6.00 | 3.39 | 10.50 | 8.69  | 2.07  | 2.56 | 0.27 | 0.32  |
| UP 163     | 2.08| 0.03| 0.99| 0.20| 0.03| 41.37| 0.05| 0.04| 0.35 | 14.00| 4.11 | 12.78 | 15.59 | 4.07  | 3.11 | 0.57 | 0.53  |
| UP 164     | 2.22| 0.04| 1.06| 0.33| 0.04| 41.71| 0.04| 0.05| 0.59 | 11.00| 4.39 | 13.75 | 12.22 | 3.11  | 3.33 | 0.36 | 0.43  |
| UP 165     | 2.05| 0.03| 0.96| 0.24| 0.03| 40.77| 0.04| 0.04| 0.40 | 17.00| 4.78 | 17.86 | 24.26 | 5.55  | 4.00 | 1.00 | 0.66  |
| Detam 1    | 2.11| 0.06| 1.00| 0.42| 0.06| 42.25| 0.04| 0.05| 0.65 | 18.00| 4.28 | 13.11 | 17.16 | 4.07  | 2.44 | 0.54 | 0.55  |
| Detam 3    | 2.18| 0.09| 1.01| 0.62| 0.09| 41.81| 0.04| 0.07| 0.75 | 17.00| 4.11 | 11.86 | 13.34 | 3.50  | 2.33 | 0.35 | 0.44  |
| GH Detam 5 | 1.92| 0.06| 0.91| 0.42| 0.06| 42.37| 0.04| 0.05| 0.62 | 23.00| 3.39 | 8.25  | 16.50 | 5.50  | 3.78 | 1.00 | 1.10  |

| Rank       | Y   | s²d | b | Wi² | σ² | CV | θ | θi | ASV | YSI | S(²) | S(³) | S(IV) | NP(²) | NP(³) | NP(IV) |
|------------|-----|-----|---|-----|----|----|---|----|-----|-----|------|------|--------|-------|-------|--------|
| A-4A-PSJ   | 11  | 6   | 9 | 6   | 6  | 2  | 6 | 8  | 4   | 8   | 12   | 12   | 13     | 13    | 10    | 13     |
| A-5A-PSJ   | 6   | 1   | 7 | 1   | 1  | 9  | 1 | 13 | 3   | 3   | 10   | 8    | 6      | 5     | 4     | 2      |
| A-7A-PSJ   | 1   | 12  | 12 | 12  | 12 | 13 | 12| 2  | 13  | 6   | 8    | 10   | 3      | 3     | 13    | 4      |
| A-8A-PSJ   | 12  | 9   | 13 | 9   | 1  | 9  | 5 | 8  | 12  | 4   | 3    | 8    | 10     | 8     | 10    | 11     |
| DB-96-CTY  | 3   | 2   | 10| 3   | 3  | 10 | 3 | 11 | 5   | 2   | 3    | 2    | 1      | 2     | 6     | 3      |
| UP 161     | 9   | 3   | 2 | 2   | 2  | 6  | 2 | 12 | 1   | 4   | 5    | 5    | 5      | 5     | 6     | 1      |
| UP 162     | 4   | 5   | 5 | 5   | 5  | 3  | 5 | 9  | 2   | 1   | 1    | 4    | 2      | 1     | 4     | 1      |
| UP 163     | 8   | 4   | 3 | 4   | 4  | 5  | 4 | 10 | 6   | 7   | 6    | 7    | 9      | 8     | 6     | 9      |
| UP 164     | 2   | 8   | 8 | 8   | 8  | 7  | 8 | 6  | 9   | 5   | 11   | 11   | 4      | 4     | 8     | 6      |
| UP 165     | 10  | 7   | 6 | 7   | 4  | 7  | 7 | 7  | 9   | 13  | 13   | 12   | 12     | 12    | 12    | 11     |
| Detam 1    | 7   | 11  | 10| 10  | 10 | 10 | 4 | 11 | 11  | 9   | 9    | 9    | 11     | 9     | 3     | 8      |
| Detam 3    | 5   | 13  | 4 | 13  | 13 | 8  | 13| 1  | 12  | 10  | 6    | 6    | 7      | 7     | 7     | 2      |
| GH Detam 5 | 13  | 10  | 11| 11  | 11 | 12 | 11| 3  | 10  | 13  | 1    | 1    | 10     | 11    | 11    | 13     |

Y = yield; SR=Sum of rank; AR=Average of rank; SD = Standard deviation

Table 4. correlation of parametric and non-parametric stability measurements to soybean grain yield
| Y  | S²¹ | S²² | S²³ | S²⁴ | NP²¹ | NP²² | NP²³ | NP²⁴ | K R | W²² | s² | s³d² | b² | CVi | β² | β³ | A |
|----|-----|-----|-----|-----|------|------|------|------|-----|-----|----|------|----|-----|----|----|---|
| Y  | 1.00|     |     |     |      |      |      |      |     |     |    |     |    |     |    |    |   |
| S²¹| -0.06| 1.00|     |     |      |      |      |      |     |     |    |     |    |     |    |    |   |
| S²²| -0.16| 0.95| 1.00|     |      |      |      |      |     |     |    |     |    |     |    |    |   |
| S²³| 0.76 | 0.45 | 0.38| 1.00|      |      |      |      |     |     |    |     |    |     |    |    |   |
| S²⁴| 0.86 | 0.35 | 0.26| 0.96| 1.00|      |      |      |     |     |    |     |    |     |    |    |   |
| NP²¹| 0.15| 0.27 | 0.32| 0.26| 0.33| 1.00|      |      |     |     |    |     |    |     |    |    |   |
| NP²²| 0.81| 0.29 | 0.24| 0.86| 0.94| 0.44| 1.00|      |     |     |    |     |    |     |    |    |   |
| NP²³| 0.76| 0.15 | 0.12| 0.82| 0.90| 0.55| 0.92| 1.00|     |     |    |     |    |     |    |    |   |
| NP²⁴| 0.87| 0.31 | 0.22| 0.96| 0.98| 0.29| 0.94| 0.90| 1.00|     |    |     |    |     |    |    |   |
| K R| 0.63 | -0.09| -0.10| 0.62| 0.72| 0.31| 0.67| 0.83| 0.69| 1.00|    |     |    |     |    |    |   |
| W²²| -0.01| -0.02| 0.07| 0.23| 0.25| 0.35| 0.24| 0.49| 0.21| 0.75| 1.00|    |     |    |     |    |    |   |
| s² | -0.01| -0.02| 0.07| 0.23| 0.25| 0.35| 0.24| 0.49| 0.21| 0.75| 1.00|    |     |    |     |    |    |   |
| s³d² | -0.01| 0.04 | 0.13| 0.25| 0.26| 0.28| 0.25| 0.48| 0.23| 0.74| 0.99| 0.99| 1.00|    |     |    |   |
| b² | 0.05 | 0.13 | -0.18| -0.15| 0.02| 0.71 | 0.10| 0.27| 0.03| 0.22| 0.25| 0.25| 0.15| 1.00|    |     |   |
| CVi | -0.40| -0.11| -0.13| -0.25| -0.30| 0.05| -0.33| -0.10| -0.21| -0.05| 0.31| 0.31| 0.28| 0.05| 1.00|    |   |
| β² | -0.01| -0.02| 0.07| 0.23| 0.25| 0.35| 0.24| 0.49| 0.21| 0.75| 1.00| 1.00| 0.99| 0.25| 0.31| 1.00|   |
| β³ | 0.01 | 0.02 | -0.07| -0.23| -0.25| -0.35| -0.24| -0.49| -0.21| -0.75| -1.00| -1.00| -0.99| -0.25| -0.31| -1.00| 1.00|
| ASV | -0.17| 0.11 | 0.14| 0.16| 0.15| 0.37| 0.15| 0.40| 0.13| 0.59| 0.91| 0.91| 0.90| 0.24| 0.52| 0.91| -0.91| 1|
| YSI | 0.64 | 0.06 | 0.00| 0.74| 0.80| 0.31| 0.74| 0.88| 0.78| 0.94| 0.70| 0.70| 0.70| 0.14| 0.03| 0.70| -0.70| 0

Bold numbers correlate positively and significantly at the 5% level

Table 5. Eigenvalue, percent, and cumulative of stability measurements

| PC | 1   | 2   | 3   | 4   |
|----|-----|-----|-----|-----|
| Eigenvalue | 9.13 | 4.79 | 2.21 | 1.56 |
| Percent (%)  | 48.07 | 25.23 | 11.62 | 8.22 |
| Cumulative (%) | 48.07 | 73.30 | 84.92 | 93.14 |

PC = Principal Component

Table 6. Parametric and non-parametric stability measurements
### Parametric stability measurements

#### Linear regression
\[ b_1 = 1 - \frac{\sum (x_{ij} - \bar{x}_j + \bar{x}_i)(\bar{x}_j - \bar{x}_i)}{\sum (x_{ij} - \bar{x}_j)^2} \]
Eberhart and Russel

\[ s^2_{b1} = \frac{1}{N-2} \left[ \sum (x_{ij} - \bar{x}_j - \bar{x}_i + \bar{x}_j)^2 \right] - (b_1 - \bar{b})^2 \left[ \sum (\bar{x}_j + \bar{x}_i)^2 \right] \]
Plaisted and Peterson

#### Mean variance component (b1)
\[ \theta_{11} = \frac{p}{2(p-1)(q-1)} \sum (x_{ij} - \bar{x}_j + \bar{x}_i)^2 + \frac{SSGE}{2(p-2)(q-1)} \]
Plaisted

#### GE variance component (b2)
\[ \theta_{21} = \frac{-p}{(p-1)(2q-1)} \sum (x_{ij} - \bar{x}_j + \bar{x}_i)^2 + \frac{SSGE}{(p-3)(q-1)} \]
Plaisted

#### Eovariance value (W)
\[ W_p^2 = \sum (x_{ij} - \bar{x}_j - \bar{x}_i + \bar{x}_j)^2 \]
Wricke and Weber

#### Shukla's stability variance (pST)
\[ p^{ST} = \frac{p}{(p-2)(q-1)} \left[ \frac{W_p^2}{(p-3)(q-1)} \right] \]
Shukla

#### Coefficient of variance (CV)
\[ CV = \frac{\text{MAD}}{\bar{x}} \times 100 \]
Francis and Kannenberg

#### Yield Stability Index (YSI)
\[ YSI = RAVS + RGY \]
Kang

### Non-parametric stability measurements

#### Nassar and Huerlin
\[ s_{11}^{(1)} = \frac{2}{N(n-1)} \sum_{i=1}^{N} \sum_{j=1}^{n} (x_{ij} - \bar{x}_j)^2 \]
Huerlin, Nassar and Huerlin

\[ s_{11}^{(2)} = \frac{(N-1)}{N} \sum_{i=1}^{N} (x_{ij} - \bar{x}_j)^2 \]

\[ s_{11}^{(3)} = \frac{1}{N} \sum_{i=1}^{N} (x_{ij} - \bar{x}_j)^2 \]

\[ s_{11}^{(4)} = \frac{1}{N} \sum_{i=1}^{N} (x_{ij} - \bar{x}_i)^2 \]

#### Thienhaus
\[ N_P^{(1)} = \frac{\sum (x_{ij} - M_x) - M_x}{N} \]
Thienhaus

\[ N_P^{(2)} = \frac{\sum (x_{ij} - M_x)}{M_x} \]

\[ N_P^{(3)} = \frac{\sum (x_{ij} - M_x)}{M_x} \]

\[ N_P^{(4)} = \frac{2 \sum (x_{ij} - M_x)^2}{(N-1)} \]
Kang

\[ X = \text{grain yield total of } i^{th} \text{ line in } j^{th} \text{ environment}; \bar{x}_i = \text{average of the grain yield total from } i^{th} \text{ line at all (three) environments}; \bar{x}_j = \text{average of the grain yield in the } j^{th} \text{ environment}; \bar{x} = \text{average of the grain yield total}; p \text{ and q are numbers of environments and lines; SD} = \text{standard deviation of GEIs}; \tau_i = \text{stability rank of the } i^{th} \text{ line in the } j^{th} \text{ environment}; \tau_j = \text{average rank if } j^{th} \text{ line in all environments}; \text{ and } N = \text{number of environment}. \]

\[ RGY = \text{rank of grain yield}; \text{Rav} = \text{Rank of Shukla stability measurement}. \]

### Figures

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Figure 1

GEl's Box plot from eight environments on 13 soybean lines in Indonesia. E1 = Ngawi (2016), E2 = Banyuwangi (2016), E3 = Banyuwangi (2017), E4 = Ngawi (2017), E5 = Probolinggo (2018), E6 = Malang (2018), E7 = Bantul (2019), E8 = Bogor (2019).
Figure 2

GEIs heatmap from eight environments on 13 soybean lines in Indonesia. E1 = Ngawi (2016), E2 = Banyuwangi (2016), E3 = Banyuwangi (2017), E4 = Ngawi (2017), E5 = Probolinggo (2018), E6 = Malang (2018), E7 = Bantul (2019), E8 = Bogor (2019)

Figure 3

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Clustering of soybean lines based on parametric and non-parametric measurements in Indonesia

Figure 4

Principal Component Analysis (PCA) of parametric and non-parametric stability measurements on soybean lines in Indonesia
Figure 5

AMMI biplot PC1 vs PC2 on 13 soybean lines in Indonesia during 2016-2019
Figure 6

AMMI biplot PC1 vs Yield on 13 soybean lines in Indonesia during 2016-2019
Figure 7

Mega-environments on 13 soybean lines in Indonesia during 2016-2019