Research Article

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Stability and adaptability analyses to identify suitable high-yielding maize hybrids using PBSTAT-GE

https://doi.org/10.1515/opag-2025-0447
received February 3, 2025; accepted May 8, 2025

Abstract: An assessment of the stability and adaptability of released varieties is needed to ensure their potential. Analysis of both approaches can be performed through PBSTAT-GE. However, the application of PBSTAT-GE in combination with index selection for elucidating stability and adaptability in hybrid maize has not been reported in depth. Therefore, this study aimed to identify suitable high-yielding maize hybrids based on stability and adaptability analyses using PBSTAT-GE software followed by index selection. The study was conducted in eight locations having different agro-climates in 2023, including eight test hybrids and two check varieties. The experiment used a randomized complete block design with three replications in each environment, so there are 300 experimental units in this study. This study focused on the grain yield, which was analyzed for potential stability and adaptability in the PBSTAT-GE. Based on the results of this study, PBSTAT-GE has the potential to be applied for comprehensive stability and adaptability analysis. The max–min standardization-based accumulation index can combine parametric stability-based assessment, non-parametric stability, and productivity potential of a genotype. Based on this approach, MAI-UH 08 and MAI-UH 03 are recommended for hybrid maize variety release with good stability and adaptability potential in both. In addition, lines MAI-UH 01, MAI-UH 02, and MAI-UH 05 can be recommended in Tomohon and Boyolali based on good adaptability potential. In conclusion, PBSTAT-GE is highly suitable and recommended for stability and adaptability analysis in identifying high-yielding maize hybrids, especially using a max–min standardization-based accumulation index.

Keywords: adaptability, GGE, parametric stability, non-parametric stability, *Zea mays*

1 Introduction

Maize is an essential crop that contributes to the world economy. This is evidenced by global maize production reaching 1.2 billion tons by 2023, which has had the fastest growth since 2010 (46%) compared to other significant cereals [1]. The United States is the leading producer, with about 32.07% of the world's corn production, followed by China at 23.74% and Brazil at 7.51%. Meanwhile, Indonesia is the sixth-best producer in the world with 2.4%. This shows that maize is essential to Indonesia's economy [2]. The potential of maize as food, feed, and industrial material is an attraction in its development [3–5]. Among these, maize's potential as feed has the most considerable contribution, reaching 70% of Indonesia's commodity use [6]. The high demand for poultry protein increases the demand for maize feed yearly, along with population growth [7]. Particularly in Indonesia, the demand for poultry protein reaches 1.62 million tonnes per year, resulting in the need for maize for feed, reaching 11.27 million tonnes or

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about 77.92% of the total maize demand in 2023. This can be seen from the volume of imports, which reached 1.23 million tonnes or about 8.31% of total production [8]. In the light of above fact, the development of maize intensification is the leading solution to boosting national maize production.

Basic intensification development can be done by genetic improvement of plants [9,10]. As a cross-pollinated crop, maize will utilize the potential of heterosis to support high productivity [11–13]. The increase in heterosis highly depends on epistasis over dominance between maize alleles [13,14]. It is because hybrid maize is a cross between two homozygous pure strains, so their cross will produce heterozygous genetic constructs that are dominant in almost all genes. This is in contrast to open-pollinated, which still allows inbreeding depression in some genes [9,10,15,16]. This phenomenon makes the development of hybrid maize more popular [15–19]. This is also supported by maize seed market data, where hybrid maize varieties have a dominant contribution, reaching >90% of the total maize seed trade [20]. Therefore, maize development has focused more on developing hybrid maize than open-pollinated maize.

Hybrid maize development is done systematically through diversity establishment, selection, and evaluation [21]. Among the three, the potential genotypes evaluation stages are positioned toward the final stages of the variety development activities [22,23]. This stage consists of several types of evaluation, namely preliminary, advanced, and multilocation trials [21,22]. The concept of multilocation evaluation is the last evaluation stage before being recommended for variety release [21,22,24,25]. The analysis concept in this evaluation is highly complex because it involves GxE interactions, stability, and adaptability [18,25]. Therefore, systematic analyses in this evaluation are needed to support the potential productivity and stability of the hybrid lines to be released.

The concepts of stability and adaptability are considered in varietal releases [25–28], including hybrid maize [18,29,30]. Released varieties are expected to have high potential and be stable in several regions [18,28,30]. This stability guarantees that a seed company will sell seeds of its superior varieties [26,31]. The potential for stability can be reflected in the pattern of genotype interaction responses to the environment, so stability analysis is often carried out in multilocation evaluations [30–33]. However, this potential needs to be matched with its adaptability potential [25–27,29,34]. Adaptability potential is closely related to the economic potential of a genotype in an environment. A genotype that is considered unstable is still valuable if the potential of the genotype provides economic benefits [25,27,35]. Moreover, genetically, the genotype has significant interactions with a particular environment [30,31,34,35]. This has become a benchmark for some farmers in determining which varieties to plant [34,35]. Hence, determining both potentials is equally vital in the multilocation-based evaluation process. Estimation of stability and adaptability can be done with various software. One of them is PBSTAT-GE.

PBSTAT-GE is a web-based software that offers genotype-by-environment interaction (GEI) analysis, including stability and adaptability and belongs to the PBSTAT software group [36]. The advantages of this software focus on the many approaches offered in stability and adaptability analysis, both image-based and formulation-based [25,37]. It has also been applied to several crops, such as rice [25,37,38], maize [34], wheat [39], and areca nut [40]. However, the utilization of maize has not been exposed in much detail, especially when looking at the effectiveness of this software. In addition, the process of simplifying the complexity of the analysis results offered still needs to be developed. PBSTAT-GE software version 3.5 offers 41 stability analysis formulation approaches, both parametric and non-parametric [41]. This makes the analysis results complex and comprehensive, so the interpretation concept must be simplified. Keeping in view the above facts, developing the idea of stability and adaptability analysis based on PBSTAT-GE software must be optimized for hybrid maize lines. This research aims to identify suitable high-yielding maize hybrids based on stability and adaptability analyses using PBSTAT-GE software followed by index selection.

2 Materials and methods

2.1 Experimental design

Multilocation testing was conducted in eight locations having different agro-climates in 2023. These differences included soil and land types, various climate types, and the altitude of the experimental locations. Specifically related to site altitude, this experiment covered three types: lowland from 31 to 166 m above sea level, midland from 434 to 627 m above sea level, and highland from 501 to 997 m above sea level. All information regarding the environment is shown in Table 1. As for the test material, the genetic material used consisted of eight candidate hybrid maize varieties, namely MAX-UH 01, MAX-UH 02, MAX-UH 03, MAX-UH 04, MAX-UH 05, MAX-UH 06, MAX-UH 07, and MAX-UH 08 and two check varieties, BISI 18 and P 36. All

Table 1: Description of test environment of maize hybrids multilocation trials

No.	Locations	Land type	Soil type[a]	Elevation (m asl)	Climate type[b]	Planting date	Harvesting date
1	South Sulawesi, Bone	Paddy field	Alfisol	31	E1	28-Feb-23	11-Jul-23
2	East Java, Probolinggo	Dry field	Latasol	93	C3	14-Mar-23	17-Jul-23
3	East Java, Jember	Paddy field	Alluvial	166	D1	15-Apr-23	1-Aug-23
4	Central Java, Boyolali	Dry field	Latasol	507	C1	28-Apr-23	2-Aug-23
5	North Sulawesi, Minahasa	Dry field	Regosol Grey	501	C2	23-Apr-23	15-Aug-23
6	Central Java, Klaten	Dry field	Regosol Grey	543	C2	2-May-23	17-Aug-23
7	North Sulawesi, Tondano	Dry field	Grumosol	801	D1	14-Apr-23	20-Aug-23
8	North Sulawesi, Tomohon	Dry field	Andosols	997	D1	8-Apr-23	20-Aug-23

Notes: a = Soil classification according to the National Soil Classification Technical Guidelines, b = Climate type classification according to Oldeman.

genotypes were planted in each environment using a randomized complete block design with three replications at each location.

2.2 Research procedure

The procedure followed the general method of maize cultivation used by Azrai et al. [18,34]. The first step was complete tillage. Next, plots measuring 2.8 m × 5 m were planted with a spacing of 70 cm × 20 cm. Each planting hole was filled with two seeds. Thinning was done, leaving one plant per clump. Furthermore, maize plants were managed through weeding, fertilization, pest control, and harvesting. Weeding was done with selective herbicides after the first fertilization. Herbicide spraying was done when the soil was moist enough. Tilling was done after the second fertilization by raising the soil mound and loosening the soil to improve aeration. Fertilization included 150 kg/ha urea and 350 kg/ha NPK (15:15:15), applied 10 days after transplanting, followed by an additional 200 kg urea in 35 days after transplanting.

Pest control was done through targeted application of pesticides based on the type of pest present. Harvesting was done at physiological maturity, forming a black layer at the base of the seed. It was done manually in the middle of the two rows of plants per number, then processed to observe yield components.

2.3 Observation parameters and data analysis

The data were analyzed with PBSTAT-GE software version 3.5 (www.pbstat.com). The analysis results from the software include ANOVA, AMMI, GGE, and stability analysis with parametric and non-parametric approaches. The GGE analyses chosen were which-won-where and mean vs stability analyses. Both can be combined to assess potential adaptability and understanding. Potential genotypes in each formulation stability analysis approach, both parametric and non-parametric, were ranked. The rankings are converted into index values according to the approach of Anshori et al. [25] to measure stability. Meanwhile, the combined stability of the two approaches was averaged first. The average became the subtractor to the yield index in forming the adaptability index.

3 Results

The results of variance analysis for each environment and their combinations are shown in Table 2. Based on the data, all environments showed a CV of less than 15%. The average productivity of all environments was 10.55 tonnes/ha. Klaten was the environment with the highest productivity (12.75 tonnes/ha), while the environment with the lowest productivity was Bone (9.01 tonnes/ha). Based on the effect of the source of diversity, all environments were significantly influenced by genotype diversity, except for Klaten and Tomohon. In addition, productivity was also significantly influenced by the diversity of GxE interaction. Meanwhile, based on the heritability value, the combination heritability showed a high heritability of 74.93%, with the highest heritability belonging to the Bone environment (93.84%).

The analysis results in the PBSTAT-GE software are presented in two forms of interpretation, namely images (AMMI and GGE) and tables. Based on AMMI stability analysis, several genotypes are inside the circle: MAI-UH 03, MAI-UH 04, MAI-UH 08, BISI 18, and Pioneer 36 (Figure 1). In contrast, the genotypes MAI-UH 01, MAI-UH 06, and MAI-UH 07 were far outside the circle. Based on the environment, Bone and Jember were located inside the circle, and Minut and Tomohon were environments with diversity far outside the circle.

Table 2: Analysis of variance of ten maize hybrids evaluated in ten locations

Genotype	Bone	Boyolali	Jember	Klaten	Minut	Muneng	Tomohon	Tondano	Mean
BISI 18	8.65	11.87	8.33	12.27	11.57	9.69	9.24	10.73	10.29
MAI-UH 01	10.12	13.91	9.13	13.77	10.92	9.77	10.59	11.15	11.17
MAI-UH 02	9.14	11.22	8.78	12.23	11.69	9.29	9.04	11.58	10.37
MAI-UH 03	9.48	12.33	10.73	13.78	12.13	9.23	10.35	11.79	11.23
MAI-UH 04	6.76	10.23	8.20	12.57	9.78	9.10	7.22	11.44	9.41
MAI-UH 05	8.69	13.31	9.41	12.87	10.64	8.67	12.18	13.91	11.21
MAI-UH 06	8.43	12.71	8.90	13.00	9.61	9.87	6.98	10.29	9.97
MAI-UH 07	9.75	10.72	8.84	11.27	12.99	10.08	7.41	11.96	10.38
MAI-UH 08	9.55	12.81	9.59	13.07	12.45	9.97	9.97	12.12	11.19
P 36	9.49	11.87	8.65	12.70	11.60	8.56	8.35	10.94	10.27
Mean	9.01	12.10	9.06	12.75	11.34	9.42	9.13	11.59	10.55
LSD 0.05	0.58	1.01	0.98	1.33	1.19	1.51	1.43	1.31	0.41
CV (%)	4.55	5.92	7.64	7.36	7.43	11.31	11.07	7.99	8.05
G *p*-value	0.0000**	0.0001**	0.0139*	0.1184	0.0016**	0.6528	0.0000**	0.0120*	0.0000**
GxE *p*-value	NA	NA	NA	NA	NA	NA	NA	NA	0.0000**
Heritability (%)	93.84	87.10	70.14	47.27	80.52	0.00	87.94	71.07	74.93

Notes: *significant effect at 5% error level, **significant effect at 1% error level, NA = not available, LSD = least significant difference, CV = coefficient of variance, G = genotype effect, GxE = interaction genetic and environmental effect.

The stability analysis results with the GGE concept are shown in Figures 2 and 3. In Figure 2, the GGE analysis is directed at which-won-where. MAI-UH 01, MA-UH 03, and MAI UH 05 clustered with the direction of the Tomohon, Boyolali, Klaten, Jember, and Tondano environmental varieties. MAI-UH 07 has potential productivity in the same direction as the variety in the Minut environment. MAI-UH 08 has potential productivity in the same direction as the Bone environment. Similarly, in the Muneng environment, genotypes MAI-UH 02, P 36, and BISI 18 have productivity potential in the same direction as the environment. In addition, based on GGE with the concept of mean vs stability, MAI-UH 03 and MAI-UH 08 are genotypes considered to have good stability and productivity potential (Figure 3). This is different from MAI-UH 05, which also has good productivity potential. However, the level of stability is low or environmentally specific,

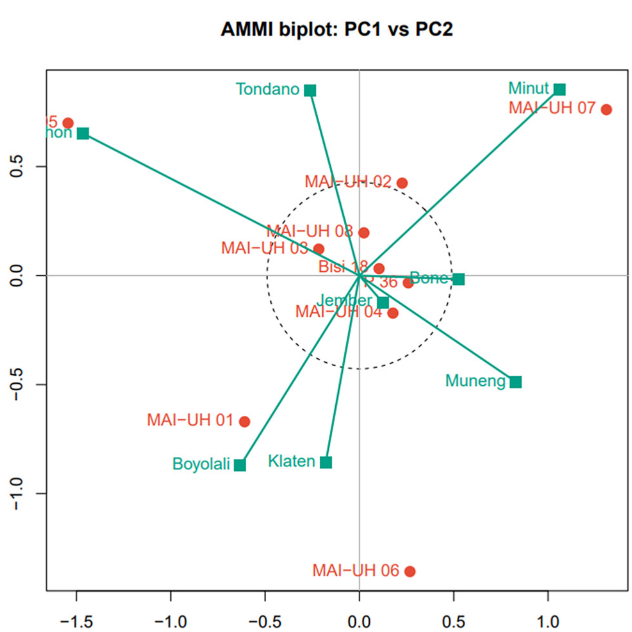

Figure 1: AMMI analysis of genotype stability in multiple environments.

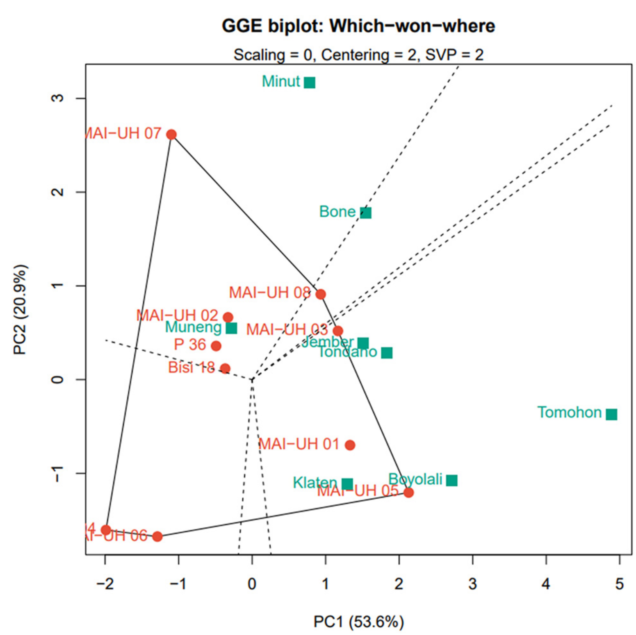

Figure 2: GGE biplot analysis: which-won-where analysis on ten maize hybrids in ten locations.

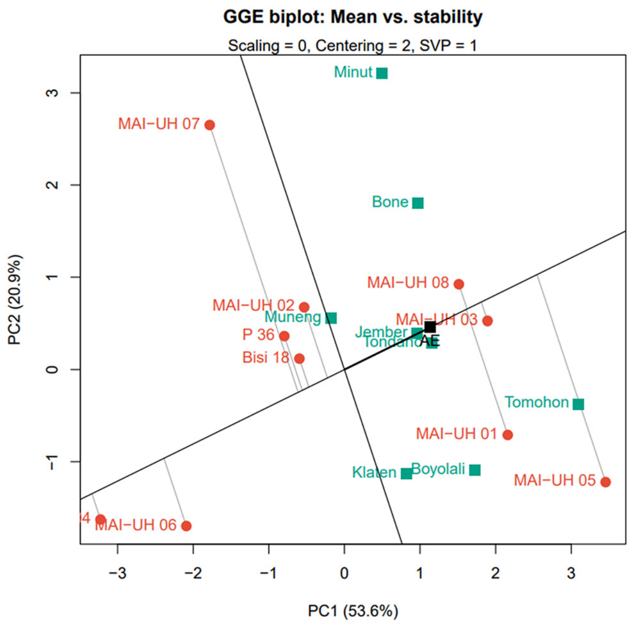

Figure 3: GGE biplot analysis: mean vs stability for ten maize hybrids in ten locations.

especially in the Tomohon and Boyolali environments. In contrast, genotypes MAI-UH 04 and MAI-UH 06 have relatively low productivity potential, although both have good stability potential. Meanwhile, based on the environment, Jember and Tondano are environments that can describe the potential mean yield and good stability compared to other environments.

The value-based stability approach is shown in Tables 3 and 4. These two tables refer to the rank index of each genotype in various stability analyses, both parametric (Table 2) and non-parametric (Table 3). Based on the parametric stability rank index analysis, MAI-UH 03 (0.20) and MAI-UH 08 (0.09) had lower rank index values than the two checks. BISI 18 and P 36 had rank index values of 0.27 and 0.46, respectively. In addition, MAI-UH 02 was also rated as potential with a lower rank index than P 35 at 0.30. In contrast, MAI-UH 05 and MAI UH 06 were rated as having the highest-ranking index of 0.82 and 0.81, respectively.

Based on Table 4, MAI-UH 02 (0.21) and MAI-UH 08 (0.11) are hybrid lines with a lower rank index than the two checks. The two checks, BISI 18 and P 36, had rank index values of 0.28 and 0.41, respectively. The hybrid line MAI-UH 03 (0.39) was also rated as potential with a lower rank index value than P 36. In contrast, MAI-UH 07 (0.81) was rated as the hybrid line with the highest rank index value in the non-parametric stability test.

Both indices are used as the basis for considering adaptability and productivity potential. The potential adaptability is displayed in the final index as shown in Table 5. Based on the table, hybrid lines MAI-UH 08 (0.88) and MAI-UH 03 (0.70) had final index values above 0.5. In addition, the hybrid lines MAI-UH 01 (0.38), MAI-UH 02 (0.28), and MAI-UH 05 (0.22), had better final index values than the two checks, BISI 18 (0.21) and P 36 (0.04).

4 Discussion

The significant effect of genotype diversity can be an early indication that the genotypes included can effectively be evaluated in multilocation. In addition, the considerable pattern also indicates that the hybrid lines tested have the potential to be better than the test varieties in this evaluation. This effectiveness was also reported by Ruswandi et al. [35], Adham et al. [32], Ma et al. [33], and Azrai et al. [18] on multilocation maize evaluation. However, the effectiveness of stability and adaptability analyses is primarily determined by the influence of interactions between genotype and environment [18,30,31,33]. A significant interaction effect illustrates that there are differences in response patterns between each genotype when grown in several environments so that genotypes that have stable and dynamic response patterns can be known in this analysis [25,27,32,35]. Based on this evaluation, the interaction effect was highly significant in the productivity tested in multilocations. This indicates that stability and adaptability analyses can be identified in this study, so PBSTAT-GE software can also be used in this multilocation evaluation.

Stability analysis in PBSTAT-GE consists of two approaches to analysis results: images and formulations. The image approach has two common types of analyses, namely AMMI and GGE. Both image analyses have specific characteristics. AMMI is focused on potential stability [25,33,37,42,43], where genotypes inside the circle are considered stable genotypes. This indicates the genotypes MAI-UH 03, MAI-UH 04, MAI-UH 08, BISI 18, and Pioneer 36 as stable genotypes. In contrast, genotypes MAI-UH 01, MAI-UH 06, and MAI-UH 07 are considered unstable. Meanwhile, based on environmental potential, Bone and Jember are considered stable compared to other environments. In contrast, Minut and Tomohon are environments with high diversity. This indicates that they are unsuitable for describing the tested genotypes' potential stability [25,37,38]. These results recommend MAI-UH 03, MAI-UH 04, and MAI-UH 08 as potentially stable hybrid genotypes in various environments. However, the potential of this AMMI also needs to be corrected with its GGE analysis.

Based on GGE analysis, MAI-UH 03 and MAI-UH 08 have good potential for stability and adaptability.

Table 3: Ranking analysis of stability index to parametric concepts

No.	Genotype	MAI-UH 01	MAI-UH 02	MAI-UH 03	MAI-UH 04	MAI-UH 05	MAI-UH 06	MAI-UH 07	MAI-UH 08	BISI 18	P 36
1	Y	4	6	1	10	2	9	5	3	7	8
2	E_{Var}	6	1	4	8	10	9	7	3	2	5
3	W^2	6	2	5	7	10	8	9	1	3	4
4	b	6	2	3	10	7	9	1	5	4	8
5	s^2d	7	2	5	6	10	8	9	1	3	4
6	D^2	6	2	5	7	10	8	9	1	3	4
7	σ^2	6	2	5	7	10	8	9	1	3	4
8	R^2	7	2	5	6	9	8	10	1	3	4
9	CV	5	1	2	10	8	9	7	3	4	6
10	GAI	3	5	1	10	4	9	6	2	7	8
11	POLAR	7	1	4	8	10	9	6	3	2	5
12	aCV	7	1	4	8	10	9	6	3	2	5
13	Pi_a	4	5	2	10	3	9	8	1	6	7
14	Pi_f	4	6	3	10	2	9	8	1	7	5
15	Pi_u	2	5	1	10	3	9	8	4	6	7
16	Wi_g	4	3	2	10	7	9	8	1	5	6
17	Wi_f	6	5	2	8	7	9	10	1	4	3
18	Wi_u	2	3	4	10	8	9	7	1	5	6
19	ASTAB	6	4	1	7	10	8	9	2	3	5
20	ASI	7	6	4	3	10	8	9	2	1	5
21	ASV	7	6	4	3	10	8	9	2	1	5
22	AVAMGE	6	4	1	7	10	8	9	2	3	5
23	Da	6	4	2	7	10	8	9	1	3	5
24	Dz	6	4	1	9	10	8	7	2	3	5
25	EV	6	4	1	9	10	8	7	2	3	5
26	FA	6	4	2	7	10	8	9	1	3	5
27	MASI	7	5	3	6	10	8	9	1	2	4
28	MASV	7	5	3	6	10	8	9	2	1	4
29	SIPC	8	4	2	6	10	7	9	1	3	5
30	Za	8	5	3	6	10	7	9	1	2	4
31	WAAS	8	5	3	6	10	7	9	1	2	4
Total		180	114	88	237	260	258	246	56	106	160
Index		0.53	0.30	0.20	0.74	0.82	0.81	0.77	0.09	0.27	0.46

Notes: Y: mean response; EVar: environmental variance; W^2: ecovalence; b: regression coefficient; s^2d: deviation from regression; D^2: genotypic stability; σ^2: stability variance; R^2: coefficient of determination; CV: coefficient of variation; GAI: geometric adaptability index; POLAR: power law residuals; aCV: adjusted coefficient of variation; Wi_g, Wi_f, Wi_u: genotypic confidence index for all, favorable, and unfavorable environments, respectively; Pi_a, Pi_f, Pi_u: superiority indexes for all, favorable, and unfavorable environments, respectively; ASTAB: AMMI-based stability parameter; ASI: AMMI stability index; ASV: AMMI-stability value; AVAMGE: sum across environments of absolute value of GEI modeled by AMMI; Da: Annicchiarico's D parameter; Dz: Zhang's D parameter; EV: sums of the averages of the squared eigenvector values; FA: stability measure based on fitted AMMI model; MASI: modified AMMI stability index; MASV: modified AMMI stability value; SIPC: sums of the absolute value of the IPC scores; Za: absolute value of the relative contribution of IPCs to the interaction; WAAS: weighted average of absolute scores.

In contrast, MAI-UH 04 has good stability potential but poor productivity. This makes MAI-UH 04 considered not adaptive. Meanwhile, MAI-UH 01 and MAI-UH 05 are considered adaptive. However, both are unstable or site-specific, especially in the Tomohon environment. The overall results of the GGE analysis sharpened the results of the AMMI analysis obtained previously. The hybrid line MAI-UH 04, considered stable in AMMI, was not adaptive in the GGE analysis. In addition, the hybrid line MAI-UH 01, considered unstable in AMMI analysis, has adaptive properties in GGE analysis. In general, GGE analysis focuses on evaluating genotype productivity (or genotype main effect) and GEI [32,44,45]. Both evaluations aim to identify genotypes that perform well across environments and genotypes that have specific adaptations to a particular environment [25,33,37,43]. These assessments deepen the study of stability analysis conducted in AMMI, so the two are always combined to assess lines' potential stability and adaptability. The effectiveness of the combination of these two approaches was also reported by Li et al. [43], Patel et al. [46], and Ma et al. [33] in

Table 4: Ranking analysis of stability index to non-parametric concepts

Genotype	YS	TOP	S1	S2	S3	S6	N1	N2	N3	N4	Total	Index
MAI-UH 01	7	3.5	6	6.5	5	4	7	10	10	10	69	0.66
MAI-UH 02	3	8.5	2	2	2	3	2	2	2	2	28.5	0.21
MAI-UH 03	1	3.5	5	5	3	2	5	7	7	7	45.5	0.39
MAI-UH 04	10	8.5	7	6.5	7	8	7	5	5	5	69	0.66
MAI-UH 05	4.5	3.5	8.5	9	8	7	7	9	9	9	74.5	0.72
MAI-UH 06	9	6	8.5	8	10	10	10	6	6	6	79.5	0.77
MAI-UH 07	8	3.5	10	10	9	9	9	8	8	8	82.5	0.81
MAI-UH 08	2	1	1	1	1	1	1	4	4	4	20	0.11
BISI 18	4.5	8.5	3	3	4	6	3	1	1	1	35	0.28
P 36	6	8.5	4	4	6	5	4	3	3	3	46.5	0.41

Notes: YS: yield and stability index; TOP: number of sites at which the genotype occurred in the top third of the ranks; S1, S2, S3, S6: Huhn non-parametric stability measures, S1: mean of the absolute rank differences of a genotype over environments, S2: variance among the ranks over the environments, S3: sum of the absolute deviations, S6: relative sum of squares of rank for each genotype; Z1, Z2: test statistics for S1 and S2, respectively; N1, N2, N3, N4: Thennarasu non-parametric stability measures.

Table 5: Adaptability analysis of some high-yielding maize hybrid lines

Genotype	Parametric index	Non-parametric index	Yield	Final index
MAI-UH 01	0.53	0.66	0.97	0.38
MAI-UH 02	0.3	0.21	0.53	0.28
MAI-UH 03	0.2	0.39	1.00	0.70
MAI-UH 04	0.74	0.66	0.00	−0.70
MAI-UH 05	0.82	0.72	0.99	0.22
MAI-UH 06	0.81	0.77	0.31	−0.48
MAI-UH 07	0.77	0.81	0.53	−0.26
MAI-UH 08	0.09	0.11	0.98	0.88
BISI 18	0.27	0.28	0.48	0.21
P 36	0.46	0.41	0.47	0.04

maize. Both analyses recommended MAI-UH 03 and MAI-UH 08 as viable lines for release as hybrid maize varieties. However, this assessment is considered too strict because it is only based on slices from both figures, so a formulation approach is needed to clarify the check of the stability and adaptability of the lines to the check varieties.

Stability analysis based on tables or formulations is divided into two approaches, namely parametric and non-parametric approaches. The parametric approach is based on the continuous distribution of data in the analysis process [42,47]. In addition, this approach emphasizes the pattern of variation that occurs in the analysis so that the potential of the tested genotypes can be directly related [42,48]. This is in contrast to non-parametric approaches. This approach focuses on discrete distributions and frequencies, so the data cannot be directly ranked [49]. Each object in the population is ranked first before being analyzed. Then, the results of the analysis become the basis for strength in check between genotypes in a population [49,50]. This method will simplify interpretation in stability analysis [51]. In addition, this analysis becomes another alternative if the assumptions of the concept of parametric stability are not met and there are data outliers in the data [37,51,52]. Based on this, both approaches are essential considerations in determining the stability pattern of a set of genotypes tested in multi-locations [25,37,51,53,54]. However, combining the two approaches requires analyzing the exact dimensions [25]. Hence, the use of index values based on standardization is essential.

MAI-UH 08 was consistently the best hybrid line based on the index results from both approaches. In contrast, MAI-UH 02 and MAI-UH 03 became the second-best hybrid lines after MAI-UH 02 in the non-parametric and parametric approaches, respectively. This illustrates that parametric and non-parametric approaches have different patterns in identifying line stability traits. Similar results were also reported by Kebede et al. [55] on oats, [53] on maize, and [56] on cotton. This difference makes it necessary to include both approaches in assessing the stability level of a genotype. Meanwhile, using selection indices is essential in unifying parametric and non-parametric stability approaches. Generally, each stability formulation has a distinctive view in assessing a genotype's potential in various environments [31,37,51,57]. Compiling all these approaches must be considered as a whole with the exact dimensions. This makes the selection index approach important [25,27,58,59].

The selection index approach can be analyzed using max–min standardization. This concept has been developed by Anshori et al. [25] in testing the stability and adaptability analysis of early maturing rice. In general, the max–min standardization approach will assess the potential of a genotype based on a ratio with a range of 0–1 [60–63]. This approach is considered more extensive because it can incorporate a combination of discrete and continuous data [25,61–63]. In the PBstat software, the concept of stability can be expressed in the form of rankings, both parametric and non-parametric based stability [25,37]. This indicates that standardization with the max–min concept is more suitable than the standardization index of normality. Particularly if the concept of stability will be continued with the concept of adaptability that takes into account its productivity potential [25]. Therefore, the concept of standardization with the concept of max–min in forming index values is suitable to be applied as an advanced analysis in the PBstat software. The results of the analysis can also be continued with adaptability analysis.

The results of the adaptability analysis showed MAI-UH 08 and MAI-UH 03 as hybrids with high adaptability potential. In addition, several other hybrids, MAI-UH 01, MAI-UH 01, and MAI-UH 05 (0.22), also had good adaptability potential compared to the two checks. The results of this potential adaptability were similar to that shown by the GGE analysis. MAI-UH 01 and MAI-UH 05 have good adaptability potential. Meanwhile, MAI-UH 02 is an additional part of the results of this analysis compared to the previous drawing approach. The results of index-based adaptability analysis have a more rational approach in considering the potential of genotypes, especially in assessing adaptability. The image-based assessment is more rigorous because it only uses slices to combine two image conclusions. In contrast, the potential of the index approach will assess rationally and objectively the potential of genotypes, both for stability and adaptability. This was also shown in the research of Sitaresmi et al. [37], Pour-Aboughadareh et al. [51], and Anshori et al. [25]. Based on this, the potential development of adaptability analysis based on the index can be used in the results of PBSTAT-GE. In addition, based on this study, hybrid lines MAI-UH 08 and MAI-UH 03 are highly recommended for releasing hybrid maize with good potential for stability and adaptability. Meanwhile, lines MAI-UH 01, MAI-UH 02, and MAI-UH 05 can be recommended on a location-specific basis with good adaptability potential, especially in Tomohon and Boyolali environments.

5 Conclusion

The use of PBSTAT-GE has the potential to be applied in comprehensive stability and adaptability analyses. Utilizing PBSTAT-GE can assess the potential of AMMI and GGE together in an image-based assessment of stability and adaptability. However, the potential of accumulation index-based assessment is considered more optimally used in the stability and adaptability assessment of PBStat results. The max–min standardization-based accumulation index can combine parametric stability-based assessment, non-parametric stability, and potential productivity of a genotype. The combination can increase precision in assessing the stability and adaptability of a genotype evaluated in multilocations. Based on this approach, MAI-UH 08 and MAI-UH 03 are recommended for hybrid maize release, which has good stability and adaptability potential. In addition, lines MAI-UH 01, MAI-UH 02, and MAI-UH 05 can be recommended on a location-specific basis with good adaptability potential, especially in the Tomohon and Boyolali environments. Meanwhile, the Jember and Tondano environments can be used to determine the potential stability of the tested lines. Based on all results, PBSTAT-GE is highly suitable and recommended for stability and adaptability analysis in identifying high-yielding maize hybrids, especially using a max–min standardization-based accumulation index. Besides, the hybrid lines recommended in this study should be continued in new, unique, uniform, and stable tests for protecting and releasing hybrid maize varieties.

Acknowledgments: This work was supported by the collaboration of the National Research and Innovation Agency (BRIN) of Indonesia and LPDP-Educational Fund Management Institution Education from the Ministry of Finance. This collaboration assistance funds our research through the scheme of Program Riset dan Inovasi untuk Indonesia Maju with grant number: 4538/UN4.22/PT.01.03.2024.

Funding information: The researchers were supported by the collaboration of the National Research and Innovation Agency (BRIN) of Indonesia and LPDP-Educational Fund Management Institution Education from the Ministry of Finance. This collaboration assistance funds our research through the scheme of Program Riset dan Inovasi untuk Indonesia Maju with grant number: 4538/UN4.22/PT.01.03.2024.

Author contributions: All co-authors reviewed and approved the manuscript before submission. All authors reviewed all the results and approved the final version of the manuscript. Conceptualization: M.A., M.F., and R.E. Data curation: M.F.A. and W.B.S. Methodology: M.A. and R.E. Software: M.F.A. and W.B.S. Validation: A.N., M.F., Y.M., and Salengke Salengke (S.S.). Formal analysis: N.F., S.B.P., M.F.A., and W.B.S. Investigation: N.F., N.N.A., B.Z., H.M., S.B.P., and Suriani Suriani (S.S.). Resources: M.A., M.F., R.E., W.B.S., and M.F.A. Data curation: R.E., M.F.A., and Suriani Suriani (S.S.).

Writing – original draft: M.A., M.F., and W.B.S. writing – review and editing: all the authors. Visualization: M.F.A., R.E., and W.B.S. Funding acquisition: M.A., M.F., and Salengke Salengke (S.S.). Supervision: A.N., Salengke Salengke (S.S.), Y.M., M.F., B.P., T.K., and S.T.

Conflict of interest: Authors state no conflict of interest.

Data availability statement: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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