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Rice cultivar selection in an agroforestry system through GGE-biplot and EBLUP

TAUFAN ALAM[1,♥], PRIYONO SURYANTO[2], SUPRIYANTA[1], PANJISAKTI BASUNANDA[1], RANI AGUSTINA WULANDARI[1], DODY KASTONO[1], MUHAMMAD HABIB WIDYAWAN[1], NURMANSYAH[1], TARYONO[1,3]

[1]Department of Agronomy, Faculty of Agriculture, Universitas Gadjah Mada. Jl. Flora No. 1, Bulaksumur, Sleman 55281, Yogyakarta, Indonesia.
Tel./fax.: +62-274-563062, ♥email: taufan.alam@ugm.ac.id
[2]Department of Silviculture, Faculty of Forestry, Universitas Gadjah Mada. Jl. Flora No. 1, Bulaksumur, Sleman 55281, Yogyakarta, Indonesia
[3]Agrotechnology Innovation Center, Universitas Gadjah Mada. Jl. Kalitirto, Berbah, Sleman 55573, Yogyakarta, Indonesia

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Abstract. *Alam T, Suryanto P, Supriyanta, Basunanda P, Wulandari RA, Kastono D, Widyawan MH, Nurmansyah, Taryono. 2021. Rice cultivar selection in an agroforestry system through GGE-biplot and EBLUP. Biodiversitas 22: 4750-4757.* Genotype-by-environment interaction (GEI) causes differences in the productivity of rice cultivars in agroforestry systems. For this reason, the stability of rice cultivars is an important aspect that should be considered before a cultivar is recommended to farmers. Superior genotypes and ideal environments are commonly identified using two statistical models, namely, genotype–genotype-by-environment biplot (GGE-biplot) and empirical best linear unbiased prediction (EBLUP). In this study, 15 rice cultivars were evaluated in terms of their productivity and stability in three soil types (Lithic Haplusterts, Ustic Epiaquerts, and Vertic Haplustalfs) in an agroforestry system with *kayu putih* (*Melaleuca cajuputi*) in 2019 and 2020 at the Menggoran Forest Resort, Playen Forest Section, Yogyakarta Forest Management District, Indonesia. The cultivars were treated as random effects to select and obtain the EBLUP of the best cultivars in each soil type. The EBLUP revealed that Situ Patenggang showed the highest yields of 4.887 and 5.456 tons ha^{-1} in Lithic Haplusterts and Vertic Haplustalfs, respectively. GM 28 exhibited the highest yield of 6.492 tons ha^{-1} in Ustic Epiaquerts. Ciherang, GM 2, GM 8, GM 11, GM 28, Inpari 6 Jete, Inpari 33, IR-64, and Way Apo Buru were classified as stable and fairly stable cultivars, whereas the other cultivars were unstable. Therefore, rice cultivars with high yields in specific soil types should be selected.

Keywords: agroforestry, *Melaleuca cajuputi*, rice cultivars, selection, soil types

Abbreviations: AEC: Average environment coordination, C•S: Cultivar-by-soil type interaction, EBLUP: Empirical best linear unbiased prediction, GEI: Genotype–environment interaction, GGE-biplot: Genotype–genotype-by-environment biplot, R: Replicate, C: Rice cultivars, S: Soil types, VCOV: Variance–covariance

INTRODUCTION

Rice is a staple food and the main source of income of farmers with land ownership of less than 1 hectare (FAO 2019). In Indonesia, rice production decreased by 4.60 million tons or 7.76% in 2019 compared with that in 2018. One of the problems related to this decline in rice production is a reduction of 10.68 million hectares or 6.15% in planting areas (Statistics Indonesia 2020). By 2045, 8.1 million hectares of rice fields in Indonesia will have been reduced to 5.1 million hectares (Mulyani et al. 2017). One alternative solution to this problem is intensifying rainfed areas in an agroforestry system for cultivating food crops, especially rice (Mulyani et al. 2017; Suryanto et al. 2020b).

Agroforestry is a land-use system and technology that integrates woody perennials with annual crops and animals in the same land management unit (FAO 2015). The potential for *kayu putih* forests in Indonesia is 248,756 hectares (Kartikawati et al. 2014). Land intensification among *kayu putih* (*Melaleuca cajuputi*) stands beneficial because the leaves and branches of *M. cajuputi* are pruned twice a year; as such, no shade effect on rice occurs and the root zone differential lessens the conflict for nutrients and water (Suryanto et al. 2020b). One solution to increase national rice production is to use superior rice cultivars with high yields and stability under various environmental conditions. Cultivars are the easiest and cheapest technologies used by farmers. Their suitability under specific environmental conditions is one of the key factors to maximize yield potential (Piepho et al. 2016). In addition, cultivars suitable for the environment streamline the input of inorganic fertilizers in compliance with the principles of sustainable agriculture (European Union 2012).

Genotype-by-environment interaction (GEI) is a phenomenon that causes differences in cultivar productivity in various environments. It causes difficulties in selecting ideal and stable cultivars for all environmental conditions (Eberhart and Russell 1966; Finlay and Wilkinson 1963; Yan et al. 2007). Nevertheless, a multi-environment trial (MET) is performed to assess the effect of GEI and select stable cultivars. This method is used to evaluate the genotype, environment, and their interactions and is composed of several statistical methods, including univariate and multivariate ones. The commonly used multivariate methods are genotype–genotype-by-environment biplot (GGE-biplot) and empirical best linear unbiased prediction (EBLUP). A GGE-biplot graph can provide visual information about the evaluation of genotype, environment, and their interactions (Yan et al. 2003; Yan et al. 2007). The GGE-biplot can be used to evaluate stability and adaptability (specific or broad) (Gerrano et al. 2020). In GGE-biplot, grain yield stability is evaluated using average environment coordination (AEC) (Bilgin et al. 2015; Oladosu et al. 2017). The EBLUP is used for a specific environment to borrow strength/information from other environments (Buntaran et al. 2019; Buntaran et al. 2020; Buntaran et al. 2021; Kleinknecht et al. 2013; Piepho et al. 2016). Alam et al. (2019a) used the EBLUP to estimate the yield of soybean varieties on various soil types in an agroforestry system with *M. cajuputi*. They showed that the Dering I variety has the highest yield in Lithic Haplusterts and Ustic Epiaquerts, whereas the Burangrang variety has the lowest yield in Vertic Haplustalfs.

This study aimed to determine the best estimate of 15 rice cultivars in an agroforestry system containing *M. cajuputi* with three soil types, namely, Lithic Haplusterts, Ustic Epiaquerts, and Vertic Haplustalfs. Thus, this study could provide farmers, scientists, and policymakers with information and options regarding stable, high-yielding rice cultivars in agroforestry systems with *M. cajuputi*.

MATERIALS AND METHODS

Study site

This study was conducted from November 2019 to February 2020 in Menggoran Forest Resort, Playen Forest Section, Yogyakarta Forest Management District, Indonesia (Figure 1a). The study site is at an altitude of ±100 meters above sea level and has a ustic moisture regime: annual mean temperature, relative humidity, and precipitation of 29.38 °C, 81.90%, and 1,182 mm year^{-1}, respectively (Alam et al. 2019a; Alam et al. 2019b; Alam et al. 2021; Suryanto et al. 2017; Suryanto et al. 2020b). This regime is composed of limited moisture but is suitable for plant growth when environmental conditions are favorable and when the water requirements for plants are met (Boettinger et al. 2015).

Multi-environment trial

A randomized complete block design factorial with five blocks as replications were prepared in three soil types (Lithic Haplusterts, Ustic Epiaquerts, and Vertic Haplustalfs). Fifteen rice cultivars were used: 11 major rice varieties (Ciherang, Inpago 4, Inpago 5, Inpago 6, Inpari 6 Jete, Inpari 33, IR-64, Puthu Gunungkidul, Situ Bagendit, Situ Patenggang, and Way Apo Buru) from the Indonesian Center for Rice Research (ICRR), West Java, Indonesia, and four promising lines (GM 2, GM 8, GM 11, and GM 28) from the Faculty of Agriculture, Universitas Gadjah Mada, Indonesia.

Experimental plots were placed between *M. cajuputi* stands of 24 m^2 (6 m × 4 m). The harvest area for rice was 20 m^2, and border crops were excluded. Minimum soil tillage was performed before the rice was planted via direct seeding with 20 cm × 20 cm spacing and two seeds per planting hole (Figure 1b). Fertilization and other cultivation techniques were implemented as recommended by the ICRR. The organic fertilizer made from cow manure of 10 tons ha^{-1} was applied before planting and urea fertilizer of 300 kg ha^{-1} was applied when the rice reached one and eight weeks after planting (WAP). SP-36 and KCl fertilization were applied at 100 and 150 kg ha^{-1} after one WAP, respectively. Irrigation was not carried out during the study as it was situated in a rainfed area.

Data collection

The observed parameter was rice yield per hectare. Rice grains were sun-dried to reach the moisture level of 11%. (Suryanto et al. 2020a; Suryanto et al. 2020b). Measuring the moisture content of the seeds using the AMTAST JV002 series grain moisture tester.

A B

Figure 1. A. Geographical locations of the study site (latitude 7º 52` 59.5992`` S to 7º 59` 41.1288`` S and longitude 110º 26` 21.462``E to 110º 35` 7.4868`` E) (Alam et al. 2019a, B. Rice cultivars between *M. cajuputi* stands

Table 1. Factors for the analysis of rice cultivars in *M. cajuputi* agroforestry system by using linear mixed models

Factors	Number of levels	Symbols
Soil types	3	S
Rice cultivars	15	C
Replicate	5	R

Statistical analysis

The following model was used (Alam et al. 2019a):

Rice cultivars × (soil types / replicate) = soil types: replicate + rice cultivars + rice cultivars • soil types

Where: fixed and random effects are indicated before and after the colon; the cross effect is denoted by the dot between the two factors; C•S is the interaction between a cultivar and a soil type; and replication is nested in the soil type. The random effects on the covariance structure for each treatment factor were described as follows:

The covariance structure for replicate (R) is $\mathbf{G}_R = \oplus_{j=1}^{J} \mathbf{G}_{R(j)}$, where $\mathbf{G}_{R(j)}$ is a diagonal matrix with diagonal elements $\sigma^2_{R(j)}$. A certain soil type variance was assumed (i). The covariance structure for the cultivar effect is the identity structure, namely, $\mathbf{G}_V = \sigma^2 \mathbf{I}$ (ii). The residual covariance structure is heterogeneous with soil type-specific $\mathbf{R} = \oplus_{j=1}^{J} \mathbf{R}_j$, where $\mathbf{R}_j$ is a diagonal matrix with $\sigma^2_{\varepsilon(j)}$ (iii)

A model was created for the variances of C•S in the baseline linear model based on the cultivar to assess the stability of cultivars. C and C•S were set as random effects to estimate the cultivar effects per soil type with borrowing strength across soil types. This estimate was called EBLUP because the cultivars were assigned a random effect. The term "empirical" was used because variance components are unknown and thus should be estimated (Littell et al. 2006).

The base model was re-parameterized by removing the main C effect, and the C•S effect was dropped using C as the subject effect to apply a different variance-covariance (VCOV) model of the C•S term. The soil type-specific genetic effects of C•S for the same cultivar were correlated between soil types. Thus, BLUPs for a specific environment can borrow information from soil types (Buntaran et al. 2019; Buntaran et al. 2020; Buntaran et al. 2021; Kleinknecht et al. 2013; Piepho et al. 2016).

Modeling based on the generalization of the variance stability model was performed to assess cultivar stability (Shukla 1972). The C and C•S effects were used as random effects to estimate the cultivar effect per soil type by borrowing information across soil types. The EBLUP and Shukla models were utilized with PROC MIXED in SAS 9.4 software (SAS Institute 2013).

Data were analyzed graphically to interpret GEIs by using the GGE-biplot technique (Yan 2007). The graphs were based on a which-won-where pattern, AEC, and a genotype-focused scaling pattern based on angles between soil type vectors. The GGE-biplot was analyzed with Genstat 18th edition (Goedhart and Thissen 2016).

RESULTS AND DISCUSSION

Site characteristics

The soil types in the study area were classified as Lithic Haplusterts, Vertic Haplustalfs, and Ustic Epiaquerts (Alam et al. 2019a; Alam et al. 2020; Alam et al. 2021; Suryanto et al. 2017; Suryanto et al. 2020a; Suryanto et al. 2020b). Lithic Haplusterts is included in Vertisol, which shrinks under dry conditions and expands under wet conditions. It is shallow (<50 cm) and has a rock contact (Boettinger et al. 2015). Vertic Haplustalfs belongs to Alfisols with a Vertic characteristic. Ustic Epiaquerts is also a Vertisol that is flooded for more than 6 months; under dry conditions, cracks form (>5 mm wide and >25 cm thick) (Soil Survey Staff 2014).

Soil analysis results showed that all soil parameters (physical, chemical, and biological) showed significant to very significant differences between soil types except the availability of Mn and Al. The soil texture in the study area was generally dominated by clay texture, the pH of H_2O was alkaline, and CEC was high. Soil organic carbon content (SOC), total N, and P availability were low, whereas K availability was moderate (Table 2) (Suryanto et al. 2020). Lithic Haplusterts and Vertic Haplustalfs were marginally suitable for rice because both tend to be rainfed areas. Ustic Epiaquerts was also favorable to rice growth because it is a flooded basin area during the wet season (Djaenudin et al. 2011).

Ranking and EBLUP of 15 cultivars in each soil type

The ranking of rice cultivars in various soil types is presented in Table 3. The EBLUP showed that Situ Patenggang showed the highest yield of 4.887 tons ha^{-1} in Lithic Haplustert, whereas Puthu Gunungkidul had the lowest yield of 2.078 tons ha^{-1}. Situ Patenggang and Puthu Gunungkidul cultivars had the highest and lowest yields of 5.456 and 2.486 tons ha^{-1} in Vertic Haplustalfs, respectively. In Ustic Epiaquerts, GM 28 had the highest yield of 6.492 tons ha^{-1}, whereas Inpago 6 had the lowest yield of 2.081 tons ha^{-1}. If the effect model remains when the ratio G2/σE2 is known, then the mean squared error of the EBLUP is smaller than that of the best linear unbiased estimates (Forkman and Piepho 2013).

The rice cultivar rankings are different among the three soil types; as such, the genetic correlation is low (Table 4). C and C•S models are random, so strength across different environments, i.e. soil types, may be borrowed. The C•S model reduces the degree of shrinkage compared with that of other models. The independent (ID) model likely has more shrinkage than the C•S model. The degree of shrinkage in the C•S model allows borrowing strength across soil types, whereas the ID model only uses information from the targeted soil type. Cultivars are set as random effects because the analysis aims to select the best cultivar in each soil type. Smith et al. (2005) stated that the estimated cultivar effect rating should be as accurate as of the actual cultivar effect rating in the selection of the best variety, which requires the best prediction for the true effect.

Table 2. Soil characteristics in this study (Suryanto et al. 2020b)

Soil characteristics	**Symbols**	**Unit**	**Soil types**		
			Lithic haplusterts	**Ustic epiaquerts**	**Vertic haplustalfs**
Physical					
Soil texture	ST	-	Clay	Clay	Clay
Bulk density	BD	g cm^{-3}	1.16	1.10	1.10
Soil moisture content	SMC	mm cm^{-1}	27.65	74.26	45.08
Permeability	h	cm h^{-1}	0.001	0.001	0.001
Chemical					
pH H_2O	pH	-	8.16	7.90	7.63
Soil organic carbon	SOC	%	1.52	1.66	1.53
Cation exchange capacity	CEC	$cmol^{(+)}$ kg^{-1}	58.78	66.54	32.42
Electrical conductivity	EC	dS m^{-1}	1.69	1.91	1.06
Total nitrogen	N	%	0.13	0.18	0.12
Soil nutrient availability:					
Phosphorus	P	ppm	6.81	11.39	3.38
Potassium	K	$cmol^{(+)}$ kg^{-1}	0.41	0.50	0.31
Sodium	Na	$cmol^{(+)}$ kg^{-1}	0.63	0.66	0.12
Calcium	Ca	$cmol^{(+)}$ kg^{-1}	27.18	24.51	21.02
Magnesium	Mg	$cmol^{(+)}$ kg^{-1}	1.77	2.86	1.34
Iron	Fe	ppm	1.22	1.29	4.40
Manganese	Mn	ppm	3.25	3.37	3.61
Aluminum	Al	ppm	1.51	1.51	1.76
Biological					
Total bacteria	Bac	colony	3.43×10^6	3.57×10^6	3.47×10^6
Total fungi	Fg	colony	2.50×10^5	2.67×10^5	2.53×10^5

In the re-parameterization of the C•S model (VCOV), C is used as the subject, and the cultivar effect is excluded. The influence of genetic factors on certain soil types shows that C•S for the same cultivar is correlated with soil type; as such, the EBLUP can be used (Buntaran et al. 2019; Buntaran et al. 2020; Buntaran et al. 2021; Kleinknecht et al. 2013; Piepho et al. 2016). However, any lack of genetic correlation between environments corresponds to a GEI. Therefore, several VCOV models for C•S were fitted: ID, compound symmetry, heterogeneous compound symmetry, and UN (Piepho et al. 2016).

Rice cultivars planted on each type of soil have different yields per hectare. These differences indicate a GEI between cultivars and soil types. Genetic factors influence rice productivity in each cultivar (Klee and Tieman 2013). Giller et al. (2011) informed that different genetics between rice cultivars cause various responses to nutrient absorption, water absorption, and fertilizer application time. This finding indicates a high heterogeneity between soil types, thereby affecting the growth and yield of rice. Suryanto et al. (2020b) stated that differences in soil quality (physical, chemical, and biological) between Lithic Haplustert, Ustic Epiaquerts, and Vertic Haplustalfs cause variations in responses between rice cultivars.

Soil quality is determined by soil types and land management practices (Bilgili et al. 2017) and is considered an important element for plant growth. Each rice cultivar has different nutrient limiting factors, and rice cultivars exhibit different biochemical, physiological, and yield responses under various environmental conditions (Boy et al. 2020). The response of each rice cultivar to certain nutrients can explain why cultivars can grow well in each type of soil. Therefore, selecting the appropriate rice cultivar that can adapt to soil type can maximize the yield potential of rice cultivars and streamline inorganic fertilizer inputs (European Union 2012).

Stability variance estimates through GGE-biplot

The adaptability and stability of rice cultivars can be identified using the GGE-biplot method. In this method, the first two principal components (PC_1 and PC_2, also referred to as primary and secondary effects, respectively) are derived by subjecting the environment-centered yield data (yield variation due to GGE) to singular value decomposition (Yan et al. 2003).

Visualization with the GGE-biplot revealed eight sectors, where each sector had a vertex genotype. Two sectors had an environment, and six sectors had none. This sector with an environment is called a mega environment (Mega-E). Within this sector is a vertex genotype, which is the outermost genotype that forms a polygon when it is connected to a connection line (Farshadfar et al. 2013). The vertex genotypes consisted of GM 2 (G2), GM-28 (G5), Inpago 6 (G8), Inpari 6 Jete (G9), IR-64 (G11), Puthu Gunungkidul (G12), Situ Bagendit (G13), and Situ Patenggang (G14). The genotype had the highest or lowest yield per hectare in some or all environments because the distance of the genotype was farthest from the biplot point. Vertex genotype is the best one on the environment in the same vector; therefore, each vertex genotype has the best local adaptation in each Mega-E (Figure 1b; Yan and Kang 2003).

Table 3. Ranking, EBLUP, and standard error of 15 rice cultivars in each soil type

Soil types	Rice cultivars	EBLUP	Std. Error	df	T-value	Probability
Lithic haplusterts	Situ Patenggang	4.887	0.7272	40.8	6.72	<.0001
	GM 28	4.764	0.7272	40.8	6.26	<.0001
	GM 8	3.808	0.7272	40.8	5.76	<.0001
	GM 11	3.223	0.6564	42.4	6.14	<.0001
	Inpago 4	2.896	0.7272	40.8	5.53	<.0001
	Inpari 33	2.645	0.6564	42.4	5.83	<.0001
	Ciherang	2.629	0.7272	40.8	4.65	<.0001
	Inpago 5	2.606	0.7274	40.9	3.86	0.0004
	Situ Bagendit	2.581	0.06559	30.3	40.08	<.0001
	GM 2	2.489	0.7274	40.9	3.47	0.0012
	Way Apo Buru	2.477	0.7274	40.9	3.2	0.0027
	Inpari 6 Jete	2.248	0.6564	42.4	3.31	0.0019
	IR-64	2.153	0.7274	40.9	2.64	0.0116
	Inpago 6	2.104	0.6564	42.4	2.88	0.0062
	Puthu Gunungkidul	2.078	0.7274	40.9	1.64	0.0108
Ustic epiaquerts	GM 28	6.492	0.6555	42.1	9.86	<.0001
	GM 8	6.301	0.7277	40.9	8.79	<.0001
	Inpari 6 Jete	6.188	0.6555	42.1	8.87	<.0001
	Inpari 33	6.101	0.7277	40.9	7.12	<.0001
	GM 11	5.876	0.7277	40.9	5.84	<.0001
	GM 2	5.627	0.7273	40.8	5.8	<.0001
	Ciherang	4.965	0.6555	42.1	6.28	<.0001
	IR-64	4.919	0.7273	40.8	5.47	<.0001
	Situ Patenggang	4.070	0.7273	40.8	5.39	<.0001
	Way Apo Buru	3.117	0.7277	40.9	5.26	<.0001
	Inpago 4	2.747	0.6555	42.1	5.53	<.0001
	Puthu Gunungkidul	2.621	0.7273	40.8	4.78	<.0001
	Inpago 5	2.568	0.7273	40.8	4.68	<.0001
	Situ Bagendit	2.243	0.7277	40.9	3.84	0.0004
	Inpago 6	2.081	0.04174	30	61.53	<.0001
Vertic haplustalfs	Situ Patenggang	5.456	0.7271	40.8	7.62	<.0001
	GM 28	5.400	0.7278	40.9	7.13	<.0001
	GM 11	4.370	0.7278	40.9	7.08	<.0001
	Inpari 6 Jete	4.351	0.6558	42.2	5.98	<.0001
	Inpari 33	4.232	0.7271	40.8	5.22	<.0001
	GM 8	4.015	0.6558	42.2	5.52	<.0001
	Ciherang	3.087	0.7271	40.8	4.9	<.0001
	Inpago 4	3.086	0.7278	40.9	4.82	<.0001
	GM 2	2.973	0.6558	42.2	4.86	<.0001
	Inpago 5	2.939	0.7278	40.9	4.04	0.0002
	Way Apo Buru	2.919	0.05136	30.2	56.82	<.0001
	Situ Bagendit	2.878	0.7271	40.8	3.9	0.0004
	IR-64	2.868	0.6558	42.2	4.01	0.0002
	Inpago 6	2.535	0.7278	40.9	3.27	0.0022
	Puthu Gunungkidul	2.486	0.7271	40.8	2.1	0.0421

Table 4. Variance estimates (10^{-3} kg^2 ha^{-2}) for the C•S model

Effect†	Group	Variance estimate
R	Lithic Haplusterts	0.000033
	Ustic Epiaquerts	0.000
	Vertic Haplustalfs	0.000
C•S‡	Genetic variance (C)	0.794
	Genetic correlation§	0.742
E	Lithic Haplusterts	0.013
	Ustic Epiaquerts	0.005
	Vertic Haplustalfs	0.008

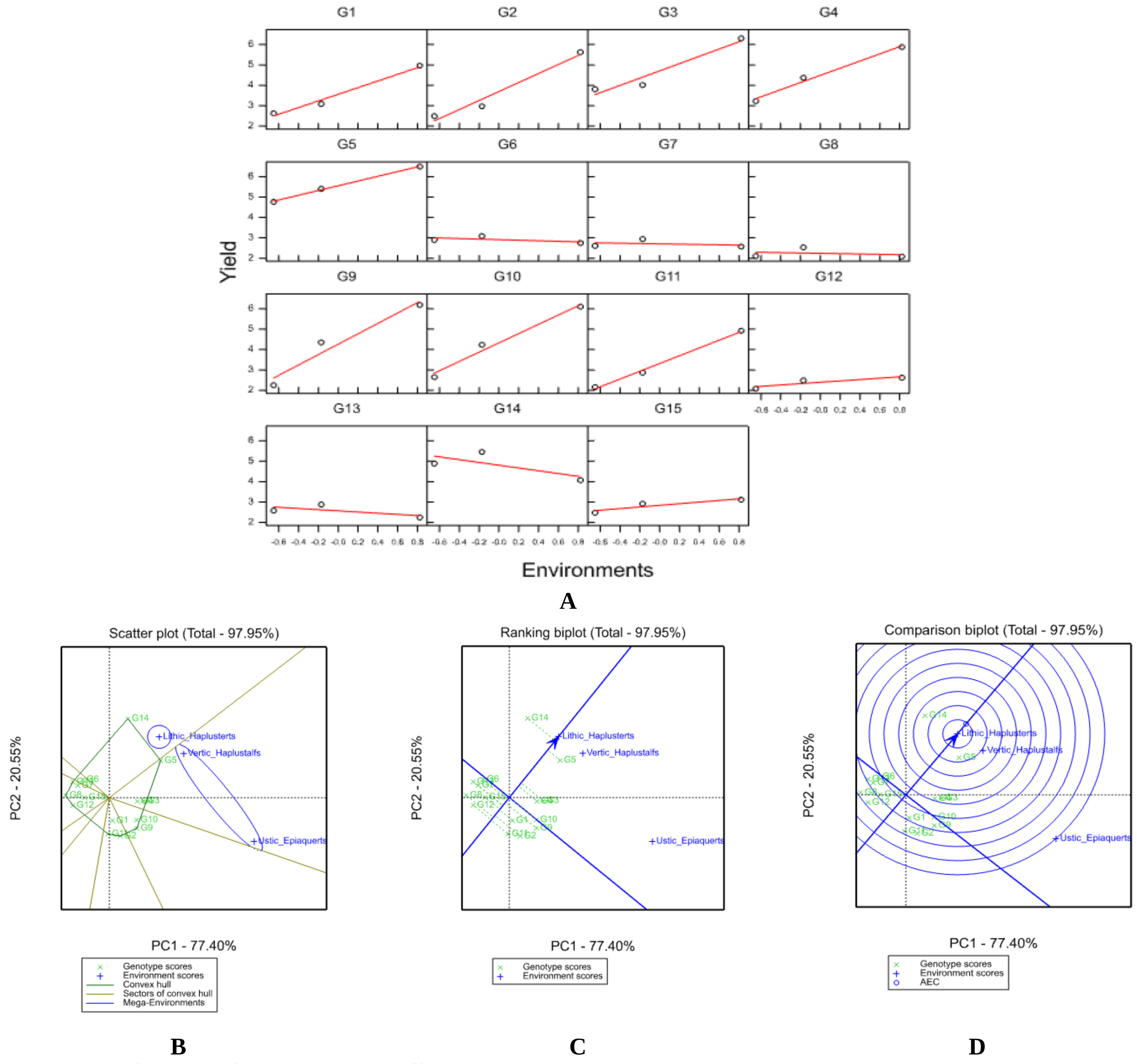
Note: †R: Replicate; C•S: Cultivar-by-soil interaction; E: error term/residual; ‡ Obtained by fitting the C•S model; § The unit does not apply to genetic correlation

The first Mega-E consisted of one environment, namely, Lithic Haplusterts, whereas the second Mega-E contained two environments, namely, Vertic Haplustalfs and Ustic Epiaquerts. Situ Patenggang (G14) exhibited the best performance in Lithic Haplusterts, whereas GM 28 (G5) had the best performance in Vertic Haplusterts and Ustic Epiaquerts (Figures 1.A and 1.B).

The stability of genotypes may be evaluated with AEC (Yan 2007). Situ Patenggang and GM 28 showed the highest mean yield in all soil types. However, genotype stability differed. The line length between the genotype and its orthogonal projection onto the biplot axis measures genotype stability. Short lines indicate high stability, whereas long lines indicate low stability. Situ Patenggang had long lines, so it was classified as an unstable cultivar. By comparison, GM 28 had short lines, so it had high stability (Figure 1.C).

The results of the GGE-biplot via the AEC method were strengthened by stability analysis with the Shukla model. This model showed that the effect of C•S varied widely between cultivars. Rice cultivars with small variance values were stable, whereas cultivars with high variance were unstable. In Table 5, the highly stable cultivars were Ciherang (0.000), GM 8 (0.045), and IR-64 (0.038); the fairly stable cultivars were GM 2 (0.192), GM 11 (0.106), GM 8 (0.207), Inpari 6 Jete (0.776), Inpari 33 (0.380), and Way Apo Buru (0.959); and the unstable cultivars were Inpago 4 (1.751), Inpago 5 (1.784), Inpago 6 (2.227), Puthu Gunungkidul (1.230), Situ Bagendit (2.297), and Situ Patenggang (3.172).

A genotype is considered ideal if it has a high mean and stability. An ideal genotype can be recommended for evaluating a specific genotype. It is found in the first concentric circle, and the desired genotype is in the second concentric circle. Genotypes in the third and subsequent concentric circles are less desirable because they have poor results (Bilgin et al. 2015; Oladosu et al. 2017). In general, no ideal genotype for rice cultivars has been identified. However, Situ Patenggang and GM 28 cultivars were included in the desired genotype (Figure 1d). No superior rice cultivar was found under all environmental conditions. Alam et al. (2019b) stated that no ideal soybean cultivar had been tested on different soil types in *M. cajuputi* forests.



A

B

C

D

Figure 1. A. Performance of rice cultivars in different soil types; B. GGE-biplot polygon with a which-won-where pattern; C. AEC shows the GGE-biplot based on the environment-focused scaling of the mean value and stability of genotype; D. GGE-biplot based on genotype-focused scaling to compare a certain genotype with an ideal genotype. G1: Ciherang; G2: GM 2; G3: GM 8; G4: GM 11; G5: GM 28; G6: Inpago 4; G7: Inpago 5; G8: Inpago 6; G9: Inpari 6 Jete; G10: Inpari 33; G11: IR-64; G12: Puthu Gunungkidul; G13: Situ Bagendit; G14: Situ Patenggang; and G15: Way Apo Buru

Table 5. Stability variance estimates (10^{-3} kg^2 ha^{-2}) for the Shukla model

Cultivars	Stability variance estimate for C•S
Ciherang	0.000
GM 2	0.192
GM 8	0.045
GM 11	0.106
GM 28	0.207
Inpago 4	1.751
Inpago 5	1.784
Inpago 6	2.227
Inpari 6 Jete	0.776
Inpari 33	0.380
IR-64	0.038
Puthu Gunungkidul	1.230
Situ Bagendit	2.297
Situ Patenggang	3.172
Way Apo Buru	0.959

Variations in genotype performance across sites are often related to differences in environmental factors, such as temperature, relative humidity, total rainfall and distribution, light intensity, photoperiod, soil moisture, and cultural practices (Azam et al. 2020; Djidonou et al. 2020). Yan et al. (2003) reported that up to 80% of variations are due to environmental influences, whereas 20% of the total variations are attributed to GEI.

Each rice cultivar has different nutrient limiting factors. Suryanto et al. (2020b) indicated that Situ Patenggang cultivar is limited by the percentage of clay in the soil. In particular, the increase in the percentage of clay in the soil is significantly correlated with the increase in Situ Patenggang yield. Situ Patenggang cultivar is a type of upland rice, so it is more adaptive to and can grow well in Lithic Haplusterts and Vertic Haplustalfs because both soil types have a low soil water content (SWC).

GM 28 cultivar is limited by SOC and SWC. The increase in the percentage of SOC and SWC in the soil is correlated significantly with the increase in GM 28 yield. SWC is an essential element for plant growth. Lack of soil moisture has an impact on drought stress in rice. Low water content can interfere with photosynthesis, reducing leaf area, cell size, and intercellular volume and ultimately lower yields (Scherer et al. 2017; Xue et al. 2017). SOC is one of the chemical properties of soil that plays an essential role in increasing plant growth and is used as an indicator to assess soil health (Brandão and Canals 2013; Brady et al. 2015). GM 28, which is a type of lowland rice, is characterized by a high yield potential if water is needed. In this study, rice cultivars were unstable and had high yields for all soil types. Therefore, location-specific rice cultivars should be selected to obtain high yields. Aristya et al. (2021) reported that GM 28 has the highest mean yield per hectare (6.980 tons ha^{-1}) in an irrigated paddy field in three districts in Central Java Province, Indonesia.

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