Additive main effect and multiplicative interaction (AMMI) stability analysis for grain yield of 27 rice genotypes tested in six environments

Aldrin Y. Cantila*[1,2], Sailila E. Abdula[1], Jenalyn B. Imbat[3], and Alvin John R. Quitel[4]

[1]Philippine Rice Research Institute, Midsayap Experimental Station, North Cotabato, Philippines
[2]School of Biological Sciences, The University of Western Australia, Perth, WA Australia
[3]PhilRice Field Office, CMU Campus, Maramag, Bukidnon, Philippines
[4]Southeast Asia Regional Initiative for Community Empowerment, Diliman, Quezon City, Philippines

Identification of rice genotypes with high stability and yield is an important aspect to the varietal recommendation of the national cooperative testing (NCT). Twenty-three rice genotypes (selection after seven generations), and the four check varieties were evaluated in grain yield (GY) to six environments. Additive main effects and multiplicative interaction (AMMI) found high significance in genotype (G), environment (E) and G by E interaction effects and in the first four interaction principal component analysis. Three public-derived genotypes: M19-250GY.3-1-2-3-4-5 (G4), M19-300GY.9-1-2-3-4-5 (G14) and M19-250GY.6-1-2-3-4 (G8), and two private-derived genotypes: Priv2-250GY.2-1-2-3-4 (G20) and Priv3-300GY.1-1-2-3-4-5 (G23) were the most stable genotypes. M19-250GY.1-1-2-3-4-5 (G2), M19-250GY.4-1-2-3-4 (G5) and M19-250GY.6-1-2-3-4-5 (G9), and two check varieties: NSIC Rc262 (G24) and NSIC Rc132 (G26) had the highest in GY. Stable genotypes can be a good gene source to breeding programs targeting rice with wider phenotypic adaptability while high yielding genotypes can be submitted for NCT. Overall, AMMI is useful in determining important variations and highly adaptable genotypes in different environments.

*Corresponding author
Email Address: aldrincantila@gmail.com
Date received: March 14, 2019
Date revised: December 30, 2019
Date accepted: February 13, 2020

KEYWORDS

AMMI model, AMMI stability index, genotype by environment interaction, grain yield, rice science

INTRODUCTION

As of December 2019, 385 rice genotypes were commercially released as varieties in the Philippines (https://www.pinoyrice.com/?wpdmdl=6337). Nevertheless, public and private rice research institutions are still in search of the best and high yielding variety. High yielding genotypes are the usual target in any crop research program (Gauch et al. 2008) that has to be locally adapted in farmer's field. Local adaptation means that genotypes have high average yield and stable yield index across locations or seasons (Abeysiriwardena et al. 1991; Annicchiarico 2002). Rice yield is largely influence by the environment. For example, multi-environment trials' data showed a variable yield in a similar genotype (Delacy et al. 1996; Yan et al. 2000; Yan and Rajcan 2002). That is why, knowledge to the genotype by environment interaction (GxE) based on phenotypic evaluation is imperative to a crop research (Umadevi et al. 2008). There are two commons models for the GxE analysis. One is the AMMI and the other is the genotype main and GxE effects (GGE). Gauch (2006) reviewed AMMI and GGE application in several researches and found that AMMI was favored over GGE. Accordingly, Gauch with co-workers (2008) reported that AMMI separates the main and interaction effects while GGE only combines G and GE, which excludes environmental effects. Freeman (1990) previously

Table 1: Twenty-seven rice genotypes as experimental materials in the study

Code	Designation/Description[1]	Code	Description[1]
G1	M19-250GY.1-1-2-3-4	G15	M19-300GY-1-2-3-4-5-1
G2	M19-250GY.1-1-2-3-4-5	G16	Priv1-250GY.1-1-2-3-4
G3	M19-250GY.3-1-2-3-4	G17	Priv1-250GY.2-1-2-3-4
G4	M19-250GY.3-1-2-3-4-5	G18	Priv1-250GY-1-2-3-4-5-1
G5	M19-250GY.4-1-2-3-4	G19	Priv2-250GY.1-1-2-3-4
G6	M19-250GY.4-1-2-3-4-5	G20	Priv2-250GY.2-1-2-3-4
G7	M19-250GY.5-1-2-3-4-5	G21	Priv2-250GY-1-2-3-4-5-1
G8	M19-250GY.6-1-2-3-4	G22	Priv2-250GY-1-2-3-4-5-2
G9	M19-250GY.6-1-2-3-4-5	G23	Priv3-300GY.1-1-2-3-4-5
G10	M19-250GY.7-1-2-3-4-5	G24*	Registered as hybrid, NSIC Rc132 on 2004 with recorded yield of 5.98 t/ha in DS and 5.85 t/ha in WS
G11	M19-250GY.8-1-2-3-4-5	G25*	Registered as hybrid, NSIC Rc202 on 2009 with recorded yield of 6.86 t/ha in DS and 6.47 t/ha in WS
G12	M19-250GY-1-2-3-4-5-2	G26*	Registered as hybrid, NSIC Rc262 on 2011 with recorded yield of 6.97 t/ha in DS and 5.92 t/ha in WS
G13	M19-250GY-1-2-3-4-5-4	G27*	Registered as inbred, NSIC Rc222 on 2009 with recorded yield of 5.83 in DS and 5.85 t/ha in WS
G14	M19-300GY.9-1-2-3-4-5		

Legend: *check varieties, G=genotype, DS=dry season, WS=wet season, NSIC= national seed industry council, [1] source: NSIC (2019), Priv1, Priv2 and Priv3=private hybrids.

reported that AMMI and its modifications used overall fitting, and it requires no limitations on the multiplicative terms and in the least square fit. Lastly, assimilating biplot presentation and AMMI stability statistics enabled researchers to decide effectively in their breeding program (Thillainathan and Fernandez 2001).

Therefore, this study was to determine significant variation of GY in 27 rice genotypes in six environments using AMMI by means of variance and principal component analyses, yield and stability rankings, and biplot analyses.

MATERIALS AND METHODS

Twenty-three inbred genotypes with their corresponding experimental codes were derived from Philippine-derived hybrids, selection after the seventh generation (Table 1). The criteria for every generation was yield-based, identifying genotypes with computed value (potential yield) ≥6.0 t/ha. Aside from the yield, the criteria included the phenotypic comparison and stability to its original source. Genotypes showing grain variation is in Figure 1. G1 to G19 genotypes were from the public hybrid, Mestiso 19, while G20 to G23 genotypes were from private hybrids, G1 to G19 genotypes were from the public hybrid, Mestiso 19, while G20 to G23 genotypes were from private hybrids.

The yield potential of each 23 genotypes was higher than the annual Philippine rice yield, which is 4.0 t/ha (https://www.pinoyrice.com/?wpdmdl=5977). The 23 genotypes and the four check varieties, NSIC Rc132, NSIC Rc202, NSIC Rc262 and NSIC Rc222 (Table 1), were set up in six environments; two seasons (dry and wet) in three Philippine Rice Research Institute (PhilRice) branch stations in Maramag, Bukidnon (E1 and E2), in Midsayap, North Cotabato (E3 and E4) and in Murcia, Negros Occidental (E5 and E6) (Table 2). The duration in months on 2017 for each station was as follows: February to May in E1, July to October in E2, January to April in E3, June to September in E4, March to June in E5, and August

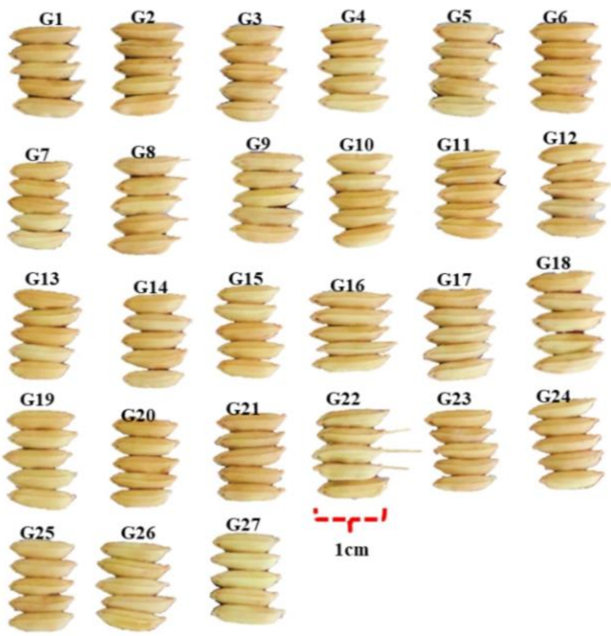

Figure 1: Grain samples of 27 rice genotypes showing the phenotypic variation. G= genotype.

to November in E6. Temperature data was taken from the weather station of the corresponding sites (Table 2). Randomized complete block design was used with three replications. The crop management was based on Palaycheck system by PhilRice (2007). The fertilizer rate was applied in the following stages: 90 kg/ha (14 N, 14 P, 14 K) and 10 kg/ha (0 N, 0 P, 60 K) during basal, 60 kg/ha (46 N, 0 P, 0 K) at tillering, and 100 kg/ha (21 N, 0 P, 0 K, 24 S) at panicle initiation. The plot was taken with yield data after. Yield data were collected from a $4m^2$ crop cut size each plot per replication with the computation of PhilRice (2007). The data was then analyzed to AMMI. It was based on a grain yield model of $Y_{ijk} = \mu + \alpha_i + \beta_j + \Sigma_N \lambda_n Y_{in} \delta_{jn} + \rho_{ij} + \varepsilon_{ijk}$, where Yijk is the actual mean yield of G i in E j; μ is the grand mean; α_i is the main effect genotype (G); β_j is the main effect environment (E); λ_n is the eigenvalue

Table 2: Six environments were described and used to evaluate 27 rice genotypes for grain yield

E	Season (Month duration)	Average temperature	Site	Longitude; Latitude	Soil type
E1	Dry (February-May)	25.6°C	PhilRice Maramag, Bukidnon	125°02'53.49"E; 7°50'51.59"N	Clay
E2	Wet (July-October)	25.3°C			
E3	Dry (January-April)	27.2°C	PhilRice Midsayap, North Cotabato	124°29'56.39"E; 7°10'48.01"N	Clay loam
E4	Wet (June-September)	27.1°C			
E5	Dry (March-June)	27.2°C	PhilRice Murcia, Negros Occidental	122°59'36.26"E; 10°34'02.11"N	Clay
E6	Wet (August-November)	26.5°C			

Legend: E=environment

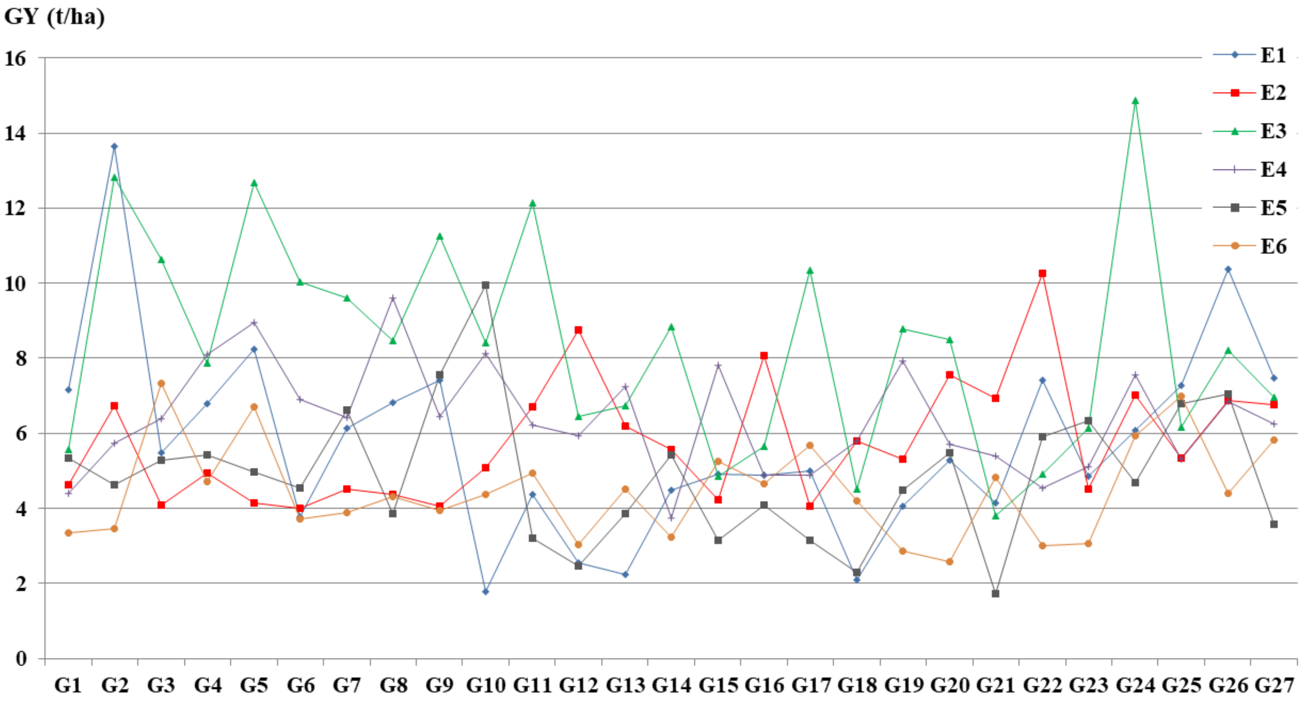

Figure 2: Twenty-seven rice genotypes showing genotypic mean yield in six environments presented in line graph. GY=grain yield, G=genotype, E=environment.

of the IPCA; n, Y_{in} and δ_{jn} are the G and E scores for the IPCA axis n; ρ_{ij} is the effect of interaction residue; N is the number of IPCA retained in the model; and ε_{ijk} is the random noise error. The AMMI stability index (ASi) was also taken using Purchase's (1997) formula: ASi= [[(IPCA1 SS/IPCA2 SS) x IPCA1 $scores^2$] + IPCA2 $scores^2$]$^{1/2}$. Statistical software such as PB Tools version 1.4 (http://bbi.irri.org/products) showed all biplot analyses and STAR version 2.0.1 (2014) for the analysis of variance and descriptive statistics.

RESULTS AND DISCUSSION

Variance and principal component analyses

AMMI method combines analysis of variance (ANOVA) and principal component analysis (PCA) because ANOVA alone fails to determine significance in interaction components while PCA fails to split significance in the sources of variation (Gauch 1988; Zobel et al. 1988). The sum of squares in AMMI had 26.8% of the total variation to environment, 5.5% to replication, 15.5% to genotypes and 52.3% to GxE. GxE was the predominant contributor of the variation. Similar conclusion in other researches like in Blanche et al. (2009) based on 15 genotypes in 10 environments, Sreedhar et al. (2011) with 17 genotypes in three environments, and Kulsum et al. (2013) with 13 genotypes in five environments. GY depends on genotype, environment, GxE, and crop management (Messina et al. 2009). The mean GY in each genotype and environment was found in Table 4. High yielding environments were in Midsayap,

Table 3: AMMI for grain yield in 27 rice genotypes in six environments were used in the GxE analysis

SV	DF	Sum of Square	Mean Square	Explained variance (%)
Environment (E)	5	752.56	150.51**	26.8
Replication/E	12	153.44	12.79**	5.5
Genotype (G)	26	435.50	16.75**	15.5
GxE	130	1470.99	11.32**	52.3
IPCA1	30	526.54	17.55**	35.8
IPCA2	28	395.75	14.13**	26.9
IPCA3	26	249.06	9.58**	16.9
IPCA4	24	197.51	8.23**	13.4
IPCA5	22	102.13	4.64ns	6.9
Pooled Error	312	1324.76	4.25	
Total	485	4137.27		

Legend: SV=source of variation, DF=degrees of freedom, ** highly significant at p ≤ 0.01, ns= not significant.

E3=8.34 t/ha and E4=6.38 t/ha while low yielding environments were in Negros, E6=4.47 t/ha and E5=4.88 t/ha. Magahud et al. (2015) reported the variable soil status for rice growing areas in the Philippines, which affects the GY. Midsayap has a clay loam soil compared to the low yielding environment with clay soil (Table 2). AMMI showed the large environmental variance, which magnifies high GxE variance. GxE variance, 10%, was higher over the combined variances in genotype and environment (Table 3). The result can be the basis to select what genotypes contain higher adaptability (Kang 1998). GxE analysis was depicted into five interaction principal component axes (IPCA) with only four IPCAs as highly significant ($p \geq 0.01$) (Table 3). IPCA1 captured 35.8%, IPCA2 with 26.9%, IPCA3 with 16.9% and IPCA4 with 13.4%. IPCA5 captured an insignificant portion of variance that accounts as noise. Admassu et al. (2008), Kaya et al. (2002) and Zobel et al. (1988) streamlined IPCA result and utilized only the two first IPCAs in the GxE analysis. Therefore, the best demonstration for the interaction of 27 rice genotypes in six environments in GY is the first two IPCA of genotypes and environments.

Yield and stability rankings

AMMI variance and PCA do not give stability measurement, which determines the variation between genotypes in each environment or changes in its relative ranking (Falconer 1952; Fernandez 1991). Hence, the yield and stability rankings were given emphasis. Yield rankings were shown in Figure 2. G2=13.64 t/ha, G26=10.37 t/ha, G5=8.24 t/ha, G27=7.47 t/ha and G22=7.43 t/ha were the top genotypes in E1. G22=10.25 t/ha, G12=8.76 t/ha, G16=8.08 t/ha, G20=7.57 t/ha and G24=7.01 t/ha were the top genotypes in E2. G24=14.87 t/ha, G2=12.81 t/ha, G5=12.68 t/ha, G11=12.15 t/ha and G9=11.26 t/ha were the top genotypes in E3. G8=9.61 t/ha, G5=8.96 t/ha, G10=8.13 t/ha, G4=8.09 t/ha and G19=7.92 t/ha in E4, G10=9.95 t/ha, G9=7.57 t/ha, G26=7.05 t/ha, G25=6.79 t/ha and G7=6.62 t/ha were the top genotypes in E5. G3=7.34 t/ha, G25=6.99 t/ha, G5=6.7 t/ha, G24=5.95 t/ha and G27=5.83 t/ha were the top genotypes in E6. Variable rankings indicate a "crossover" as described by Filho et al. (2013). It is when a rank by genotype alters from one environment to another environment. The "non-crossover" denotes a disparity change in mean yield, but not the ranking of the evaluated genotypes (Kang 1998). Over the two implications, crossover is of advantage in plant breeding because identifying genotypes can be easy (Baker 1990). Notably, few genotypes showed high GY (inclusion to the top five) in at least two environments. These genotypes were G5 (E1, E3, E4 and E5), G24 (E2, E3 and E6), G2 (E1 and E3), G9 (E3 and E5), G10 (E4 and E5), G22 (E1 and E2), G25 (E5 and E6), G26 (E1 and E5) and G27 (E1 and E6). But high GY of a genotype to at least two or more environments does not usually represent its whole stability performance; yield stability is defined as the consistency of genotypes yield response across environments (Abeysiriwardena et al. 1991; Annicchiarico 2002). With Table 4 showing a range of 0.052 to 2.481 AMMI stability index (ASi), the most stable genotypes were G4 with 0.052 ASi, G14 with 0.246 ASi, G20 with 0.325 ASi, G23 with 0.408 ASi and G8 with 0.412 ASi. The five stable genotypes had a range of 5 to 6.3 t/ha GY, GY with ≥1 t/ha over the annual rice yield of the Philippines. Thus, these genotypes can be considered to NCT trial and can be potential gene sources for having yield stability trait.

Biplot analyses

Another AMMI facet is through biplot analyses. Unlike stability index computation which is univariate (Gauch 1988; Crossa 1990) and does not present exact view of the response pattern (Hohls 1995), AMMI biplots outline inter and intra-relationships in genotypes and environments (Zobel et al. 1988; Crossa 1990). It is possibly the most powerful interpretive tool for AMMI models since both genotypes and environments are plotted on the same axes and inter-relationships can be visualized. There are two basic biplots. AMMI biplot with plotted IPCA1 and IPCA2 scores to the x and y coordinate, respectively and the AMMI biplot with main effects (genotype and environment means) vs IPCA1 scores plotted in the coordinates.

AMMI with IPCA scores in Figure 3 depicted the stability of genotypes. The first two IPCA scores were used in the computation of ASi, making ASi result parallel to the graph especially genotypes in the center point of the coordinates (Figure 4). Alberts (2004) shown genotypes with IPCA scores of lower values (+ or -) approaching zero as the widely adapted genotype to the environment while higher IPCAs explained as likely to be location-specific. It was found out that G4, G14, G20, G23, and G8 had the lowest IPCA1 and IPCA2 scores and correspondingly the lowest values in ASi (Table 4). Muthuramu et al. (2011) explained that genotypes near to the origin/center of interaction point are non-sensitive to environmental effects. Conversely, the genotypes with the highest IPCA scores G2, G22, G24, G5, and G21 were indicated as highly unstable, which proportionate as the highest ASi values. Instability is the outcome of genotype response in the varying environments, which connotes high genetic and environmental effects (Jusuf et al. 2008; Lone et al. 2009).

AMMI with main effects vs IPCA1 in Figure 4 determined genotypes with location-specific adaptability. Genotypes near to each other denote that they have near GY response and adaptation while the near plotting of environment to genotypes means that the location had mainly influenced the tested materials (Kempton 1984). Kaya et al. (2002) and Alberts (2004) made graph sections (Figure 3) based on the intersection point of GY mean and IPCA "0" score in their corresponding crop stability studies. Notably, section IV had the highest GY means, E3 among the environments and G2, G24, and G5 among the genotypes. Section II had the next highest GY means, E4 in the environment and G26 in the genotypes. Sections I and III, on the other hand, had genotypes and environments with the lowest GY means. AMMI showed few clear relationships between genotypes and environments. G2, G24, and G5 were the best genotypes in E3, G4, G8 and G10 in E4, and G22 and G16 in E2. It can be noticed too that only the top three high yielding environments (E3, E4, and E2) had near points to the genotypes, indicating location-specific adaptability in GY.

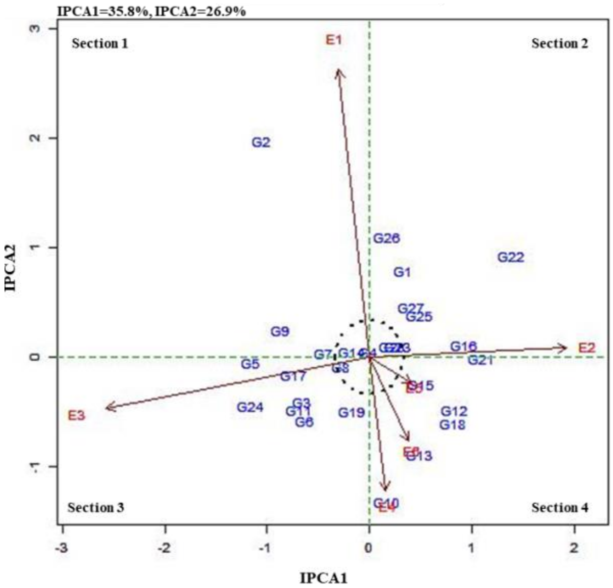

Figure 3: AMMI Biplot of 27 rice genotypes and six environments for grain yield using IPCA1 and IPCA2 scores. G= genotype, E= environment, AMMI= main effects and multiplicative interaction, IPCA= interaction principal component analysis

Table 4: Twenty-seven rice genotypes with their mean yield and its rank, AMMI stability index (ASi) and its rank, and IPCA scores were used in the study

Variables	GY (t/ha)	Rank in GY	ASi	RanK in ASi	AMMI-IPCA scores	
					IPCA1	IPCA2
G1	5.07	22	0.913	11	0.32	0.79
G2	**7.84**	**1**	2.481	27	-1.06	1.97
G3	6.54	6	1.019	12	-0.66	-0.41
G4	6.3	8	**0.052**	**1**	-0.01	0.05
G5	**7.61**	**3**	1.649	24	-1.16	-0.05
G6	5.49	18	1.076	14	-0.63	-0.59
G7	6.2	12	0.638	7	-0.45	0.03
G8	6.24	11	**0.412**	**5**	-0.28	-0.08
G9	**6.78**	**5**	1.269	18	-0.88	0.25
G10	6.29	9	1.349	22	0.16	-1.33
G11	6.26	10	1.091	15	-0.69	-0.48
G12	4.87	25	1.277	19	0.83	-0.48
G13	5.13	21	1.125	17	0.48	-0.89
G14	5.21	20	**0.246**	**2**	-0.17	0.05
G15	5.03	23	0.757	9	0.50	-0.25
G16	5.38	19	1.322	21	0.93	0.11
G17	5.52	17	1.058	13	-0.74	-0.16
G18	4.11	27	1.3	20	0.81	-0.60
G19	5.57	16	0.56	6	-0.18	-0.50
G20	5.85	15	**0.325**	**3**	0.22	0.10
G21	4.47	26	1.552	23	1.09	-0.02
G22	6.01	14	2.172	26	1.38	0.93
G23	5	24	**0.408**	**4**	0.28	0.09
G24	**7.69**	**2**	1.714	25	-1.16	-0.45
G25	6.31	7	0.789	10	0.48	0.39
G26	**7.29**	**4**	1.121	16	0.17	1.10
G27	6.14	13	0.733	8	0.40	0.46
E1	5.73	4	2.960	4	-0.33	2.92
E2	5.80	3	3.041	5	2.14	0.09
E3	8.34	1	4.092	6	-2.86	-0.53
E4	6.38	2	1.385	3	0.18	-1.36
E5	4.88	5	0.696	1	0.45	-0.27
E6	4.47	6	1.045	2	0.42	-0.86

Legend: GY= grain yield, G=genotype, E=environment, AMMI= additive main effects and multiplicative interaction, IPCA= interaction principal component analysis, bold numbers denotes belonging to top five best in GY and in ASi.

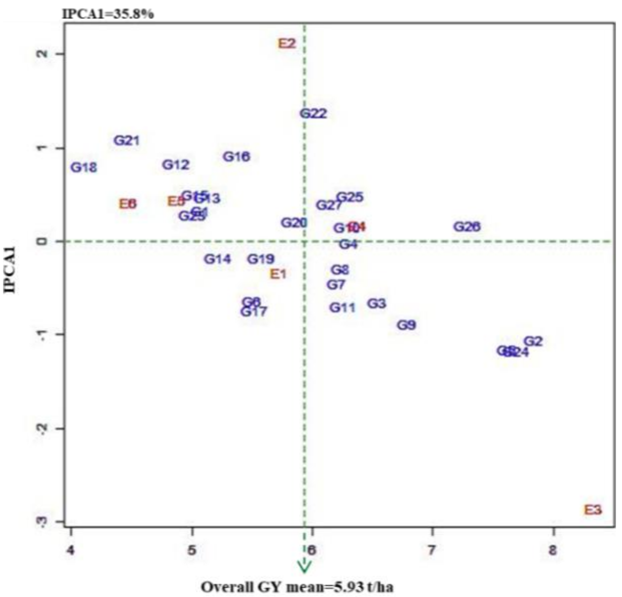

Figure 4: AMMI Biplot of 27 rice genotypes and six environments for grain yield (GY) using GYs of G and E, and IPCA1 scores. G= genotype, E= environment, AMMI= main effects and multiplicative interaction, IPCA= interaction principal component analysis.

CONCLUSION

Though AMMI detected high significant variations to known sources of variation and the first four IPCAs, AMMI for GY of 27 rice genotypes in six environments is best understood in the first two IPCAs. AMMI stability index found G4, G14, G20, G23, and G8 as the most stable genotypes with consistency to the AMMI biplot IPCA1 vs IPCA2. These genotypes can be parental materials to rice breeding programs aiming for wider phenotypic adaptability. G2, G24, G5, G26, and G9 had the highest GY (top five) with location-specific GY performance; G2, G26 and G5 in E1, G24 in E2, G24, G2, G5 and G9 in E3, G5 in E4, G9 and G26 in E5, and G5 and G24 in E6. Therefore, G2, G5, and G9 can be endorsed to the national cooperative testing of the Philippines for varietal release. G24 (NSIC Rc132) and G26 (NSIC Rc262) on the other hand, are registered hybrid varieties that can be directly promoted to farmers for planting. Overall, AMMI is useful in the determining important variations, adaptable and location-specific genotypes in several environments.

ACKNOWLEDGMENTS

The authors would like to extend their gratitude to the management of Department of Agriculture-PhilRice for the funding of this study with a project code: PBD 003-011, and title: “Development of next generation rice plant type to break yield plateau”. We would also like to thank the field workers and the staffs of PhilRice branch stations for the successful crop management.

CONTRIBUTIONS OF THE AUTHORS

AYC conceptualized the ideas, analyzed the data, prepared and finalized the manuscript, and conducted the review. SEA and JBI helped in the review and gave useful comments to the manuscript. JBI and AJRQ gathered the data and contributed to the writing of manuscript.

CONFLICT OF INTEREST

The authors affirm that the study was done without any financial or commercial relationships that could be interpreted as a potential conflict of interest.

REFERENCES

Abeysiriwardena DSdeZ, Buss GR, Reese Jr PF. Analysis of multi-environmental yield traits for testing adaptability of crop genotypes. Trop Agric 1991; 147: 85-97.

Admassu S, Nigussie M, Zelleke H. Genotype-environment interaction and stability analysis for grain yield of maize (*Zea mays* L.) in Ethiopia. Asian J Plant Sci 2008; 7: 163-169.

Alberts MJA. A Comparison of Statistical Methods to Describe Genotype x Environment Interaction and Yield Stability in Multi-Location Maize Trials. M.Sc. (Agric.) Thesis, Department of Plant Sciences (Plant Breeding), Faculty of Agriculture of the University of the Free State, Bloemfontein, South Africa, 2004.

Annicchiarico P. Genotype x environment interactions: Challenges and opportunities in plant breeding and cultivar recommendations. FAO Plant Prod Prot Paper 2002; 174: 85-86.

Baker, RJ. Crossover genotype-environmental interaction in spring wheat. In: Kang MS, ed. Genotype-by-environment interaction and plant breeding. Louisiana State University Agricultural Center, Baton Rouge, 1990: 42-51.

Blanche SB, Utomo HS, Wenefrida I, Myers GO. Genotype and environment interactions of hybrid and varietal rice cultivars for grain yield and milling quality. Crop Sci 2009; 49: 2011-2018.

Crossa J. Statistical analyses of multilocation trials. Adv Agron 1990; 44: 55-85.

DeLacy IH, Basford KE, Cooper M, Bull JK, McLaren CG. ‘Analysis of multi-environment trials – An historical perspective’. In Cooper, M., and Hammer, G.L. (eds.) Plant Adaptation and Crop Improvement. Wallingford, UK, CABI, 1996: 39-124.

Falconer DS. The problem of environment and selection. Am Nat 1952; 86: 293-298.

Fernandez GCJ. Analysis of genotype x environment interaction by stability estimates. Hort Sci 1991; 26(8): 947-950.

Filho C, de Resende JM, de Morais MDV, de Castro OP, Guimarães AP, Pereira EP, Utumi JA, Breseghello MM. Upland rice breeding in Brazil: a simultaneous genotypic evaluation of stability, adaptability and grain yield. Euphytica 2013; 192: 117 https://doi.org/10.1007/s10681-013-0922-2

Freeman GH. Modern statistical methods for analyzing genotype-environment interactions. In: Kang MS, ed. Genotype x environment interaction and plant breeding. Louisiana State University Agricultural Center, Baton Rouge, Louisiana, USA, 1990: 118-125.

Gauch HG, Piepho HP, Annicchiarico P. Statistical Analysis of Yield Trials by AMMI and GGE: Further Considerations. Crop Sci 2008; 48. 10.2135/cropsci2007.09.0513.

Gauch HG. Model selection and validation for yield trials with interaction. Biometrics 1988; 44(3): 705-715.

Gauch HG. Statistical analysis of yield trials by AMMI and GGE. Crop Sci 2006; 46: 1488-1500.

Hohls T. Analysis of genotype environment interactions. South Afric J Sci 1995; 91: 121-124.

http://bbi.irri.org/products

https://www.pinoyrice.com/?wpdmdl=5977 accessed on: 30/12/19 3:07pm

Jusuf M, Rahayuningsih SA, Wahyumi TS, Restuono J. Adaptasi dan stabilitas hasil klon harapan ubi jalar. Jurnal Penelitian Pertinian Tanaman Pangan 2008; 27: 37-41

Kang MS. Using genotype-by-environment interaction for crop cultivar development. Adv Agron 1998; 62:199–252.

Kaya MS, Palta E, Taner S. Additive main effects and multiplicative interactionss analysis of yield perfomances in bread wheat genotypes across environments. Turk J Agric 2002; 26: 275-279.

Kempton RA. The use of biplots in interpreting variety by environment interactions. J Agric Sci Camb 1984; 103: 123-135.

Kulsum MU, Hasan MJ, Akter A, Rahman H, Biswas P. Genotype-environment interaction and stability analysis in hybrid rice: an application of additive main effects and multiplicative interactions. Bangl J Bot 2013; 42(1); 73-81.

Lone AA, Sofi PA, Warsi MZ, Wani SH. Stability analysis in maize (*Zea mays* L.) for anthesis silking interval and grain yield. Maize Genet Coop Newslett 2009; 83:1-9.

Magahud JC, Badayos RB, Sanchez PB, Sta. Cruz PC. Levels and sources of potassium, calcium, sulfur, iron and manganese in major paddy soils of the Philippines. Int J Phil Sci Tech (currently Phil Sci Lett); 2015 1(2):1-8.

Messina C, Hammer G, Dong Z, Podlich D, Cooper M. Modelling crop improvement in a GxExM framework via genetic-trait-phenotype relationships. In: Sadras VO, Calderini D. ed. Crop Physiology: Applications for Genetic Improvement and Agronomy. Elvesier, Netherlands, 2009: 235-265.

Muthuramu S, Jebaraj S, Gnanasekaran M. AMMI biplot analysis for drought tolerance in rice (*Oryza sativa* L.). J Agric Sci 2011; 2: 98-100.

NSIC (National Seed Industry Council). NSIC-Approved Varieties of Rice, 2019. http://www.nseedcouncil.bpinsicpvpo.com.ph/downloadables/nsic-rice.xlsx.

PhilRice (Philippine Rice Research Institute). PalayCheck System for irrigated Lowland Rice. PhilRice, Maligaya, Science City of Muñoz, Nueva Ecija. 2007. 90 p.

Purchase JL. Parametric analysis to describe genotype x environment interaction and yield stability in winter wheat. PhD thesis, Department of Agronomy, Faculty of Agriculture of the University of the Free State, Bloemfontein, South Africa, 1997.

Sreedhar S, Dayakar TR, Ramesha MS. Genotype x Environment Interaction and stability for yield and its components in hybrid rice cultivars (*Oryza sativa* L.). Intl J Plant Breed Genet 2011; 5(3): 194-208.

STAR, version 2.0.1. Biometrics and Breeding Informatics, PBGB Division, International Rice Research Institute, Los Baños, Laguna. 2014.

Thillainathan M, Fernandez GCJ. SAS applications for Tai's stability analysis and AMMI model in genotype x environment interaction (GEI) effects. J Hered 2001; 92(4): 367-371.

Umadevi M, Veerabadhiran P, Manonmani S. Stability analysis for grain yield and its component in rice (*Oryza sativa* L.). J Rice Res 2008; 3(1):10-12.

Yan W, Hunt LA, Sheng Q, Szlavnics Z. Cultivar evaluation and mega-environment investigation based on GGE biplot. Crop Sci 2000; 40(3): 597-605.

Yan W, Rajcan I. Biplot Analysis of Test Sites and Trait Relations of Soybean in Ontario. Crop Sci 2002; 42: 11-20. 10.2135/cropsci2002.0011.

Zobel RW, Wright MJ, Gauch, HG. Statistical analysis of a yield trial. Agron J 1988; 80: 388-393.