Genotype main effects and genotype × environment interaction (GGE) analysis for grain yield of the hybrid rice varieties under rain-prone environment

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ABSTRACT

The stability of high yielding hybrid rice varieties is very important to meet food security. The grain yield (GY) stability of 13 hybrid rice varieties in multi-environment with type IV climate condition (E1, E2, E3, and E4) was analyzed using genotype main effects and genotype x environment interaction (GGE). Combined analysis of variance showed environment and genotype by environment (GxE) interaction which accounts 45% and 28% of the total variation, respectively, as the main factors influencing the GY significantly ($p < 0.005$). GGE biplots were generated using the two interaction principal components (PC1 and PC2) which accounts a total of 92.4% of the GxE effect for GY. GGE biplot analysis identified best performing genotypes for a specific environment like M1 (Mestizo 1), M60 (PAC 801), and M55 (Mestizo 55) at E1 and E2, M60 and M6 (SL-8H) at E3, and M6 at E4. M1 was ranked as top 1, M60 as top 2, M6 as top 3, and M55 as top 4 in four tested environments with a mean GY of 7.48, 7.40, 6.93, and 6.86 t/ha, respectively. Therefore, M1, M60, M6, and M55 should be recommended to rice farm areas of SOCCSKSARGEN and other places in the Philippines with type IV climate condition such as Davao regions.

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INTRODUCTION

The demand to increase the grain yield of rice will be higher in the future as consumers grow exponentially each year. Thus, switching for high yielding rice varieties like hybrid should be an option to attain higher grain yield (GY) production and food security. A total of 107 hybrid or "Mestizo" rice varieties, developed by private and public rice research institutions, were registered and commercially released in the Philippines based on National Cooperative Testing (NCT) trial results (NSIC, 2020). However, the adoption rate for hybrid rice varieties had been very low at farmer's level (Ignacio, 2019). A survey in four cropping seasons showed 95% of the 7,954 farmers do not prefer hybrid varieties (PhilRice, 2020). The low adoption rate of hybrid varieties was due to high input cost of production

KEYWORDS

GGE analysis, grain yield, hybrid rice, type IV climate

(expensive seed material and excessive reliance to agro-chemicals), rice farms don't have sufficient irrigation, most of the farmers owned small farm size, and farmers have less knowledge on hybrid farming (Digal and Placencia, 2020, FAO, 2014, Shah et al., 2014).

In the Philippines, typhoons, La Niña and other climate change effects are among the constraints in rice GY production (Alejo et al., 2021, Stuecker et al., 2018). Also, Philippines has variable rice farming climate conditions like types I and III with most months are dry season while types II and IV with most months are rainy season (PAGASA, 2014). The nutrient levels and soil properties were also significantly variable and depleted in major irrigated rice areas in the country (Magahud et al., 2016a, Magahud et al., 2016b). Thus, rice farming especially using hybrid rice varieties remains a challenge.

Rice GY is a quantitative trait which means a trait is connected to yield-related traits (PhilRice, 2007, Cantila et al., 2017). When the effect of environment is high, the genotype effect is also affected. For instance, Shah et al. (2011) reported that rice pollens will be sterile in an environment having more than 38°C temperature for at least an hour, which leads to high percentage of spikelet infertility and eventually having a low GY. Another, Cantila and Quitel (2017) and Vijayalakshmi et al. (2008) concluded that planting the same rice genotypes under multiple environments with varied amounts of solar radiation results to significant GY difference.

To dissect the effect of genetic (genotype), environment, and genotype by environment (GxE) for GY in multilocation, genotype main effects and genotype x environment interaction (GGE) can be used (Yan et al., 2007). GY, panicle length and number, spikelet number per panicle and thousand seed weight of rice were investigated using GGE analysis which led the identification of 19 desirable rice genotypes having high GY and adaptability across temperate, subtropical, and tropical conditions (Huang et al., 2021). GGE analysis also identified mega-environments suitable for upland rice genotypes at North Western Ethiopia (Tariku, 2017). Lastly, among 150 lines of Indica rice population, 15 lines were selected having drought tolerant characteristics using GGE analysis (Rahimi et al., 2013). Here, we investigate the (1) GY performance and (2) stability of the 13 hybrid rice varieties for irrigated lowland under multi-environment with type IV climate condition, which eventually (3) recommends the ideal genotype and environment for hybrid rice farming.

MATERIALS AND METHODS

Thirteen hybrid rice varieties, previously described in Cantila et al. (2019) undergone GY evaluation in multi-location (E1, E2, E3, and E4). E1 and E2 were defined in Cantila et al. (2019), E3 was set-up during October 2018 to January 2019 at Philippine Rice Research Institute (PhilRice)-Midsayap Experimental Station (MES), Midsayap, Cotabato, and E4 was set-up during April to July 2019 at Pigcawayan, Cotabato (Figure 1). E1, E2, E3, and E4 were within the SOCCSKSARGEN region with type IV climate condition (Alejo et al., 2021, PAGASA, 2014). The meteorological data of the tested environment was obtained using a climate toolbox (Hegewisch and Abatzoglou, 2020).

The detailed crop management such as the amount of fertilization, crop protection, etc. for each tested environment was also defined in Cantila et al. (2019). On the other hand, the controlled environment with normal condition (E0) was situated at PhilRice-MES screen house with the same planting duration in E1 (Figure 1). In E0, rice plants were transplanted after 21 days in 1m2 plot size randomized in three replications. In addition, full irrigation while restraining the rainfall, maximum crop protection, fertilization rate similar with the tested environments, and temperature ranging from 27 to 32°C (Yin et al., 1996) were employed to obtain a normal growth and development of the rice plants in irrigated lowland.

GY was obtained following the methodology in PhilRice (2007). The three datasets of this study (E0, E3 and E4) and two previously published datasets (E1 and E2) by Cantila et al. (2019) were used in the analysis. Combined analysis of variance (ANOVA) was based on randomized complete block design for the tested environments. For the variance percentage, the sum of squares (SS) in each variance of the ANOVA was divided to the total SS and the result was multiplied by a 100.

GGE analysis in tested environments was also computed. Furthermore, supplementary data such as descriptive statistics and GxE heat-maps were done. All statistical analyses were calculated in PBSTAT 3.0.1 (Suwarno et al., 2008).

RESULTS AND DISCUSSION

Type IV climate condition affects the GY of hybrid rice

All sources of variation (SV) were significant at $p \leq 0.01$ (Table 1). Environment (location + replication) and GxE were accounted for the 45% and 28% of the total variation, respectively (Table 1), indicating that the variation of GY was largely due to environment and not genetic. Among the environmental factors, rainy environment or wet season could influence rice GY (Wang et al, 2017, Yang et al., 2008). As observed in this study, E0 was rainfall deficit while E1, E2, E3, and E4 received an average amount of rainfall per month with 220.63 mm (Table 3). E4 received the highest amount of rainfall per month with 279 mm while E1, E2, and E3 received ≤ 246 mm amount of rainfall per month (Table 3). The genotypes at E0 had 8.74 t/ha mean GY, which was greater than their corresponding mean GY 6.83 t/ha, 6.55 t/ha, 6.12 t/ha, and 4.17 t/ha at E1, E2, E3, and E4, respectively (Table 2 and S1). Most the genotypes had their lowest GY at E4, indicating that the amount of rainfall was a factor affecting the GY of the genotypes.

Rainy weather was shown to have negative effect in Indica rice types, resulting the rice plants to be more susceptible to lodging and thereby affecting their GY (Weng et al., 2017). In GY gap analysis, rice varieties planted during dry season had 64.5% GY advantage (average in two years) over the varieties planted during rainy or wet season (Yang et al., 2008). In 2019, the rice bowl regions in the Philippines, Central Luzon and Cagayan Valley (most areas are dry season) (Alejo et al., 2021, PAGASA, 2014) produced 3.73 and 2.66 million metric tons (MMT) of rice, respectively, almost twice higher than 1.34 MMT in SOCCSKSARGEN region (most areas are rain-prone) (PSA, 2020).

Other than the amount of rainfall, the amount of solar radiation and temperature were also varied across the tested environments (Table 3). For solar radiation, E1 experienced the highest solar radiation with a mean of 207 W/m2, while E3, E4, and E2 received lesser solar radiation with ≤ 192 W/m2 (Table 3). Solar radiation may have also influenced the GY as the genotypes had their best individual GY at E1. When the amount of solar radiation is high during the rice grain filling stage, there is a chance that large photosynthates will be deposited to the grains which eventually leads to heavier grains and higher GY (Saito et al., 1991, Yang et al., 1997, Yoshida, 1972). On the other hand, temperature been shown to affect rice GY based on previous findings (Cantila and Quitel, 2017, Huang et al., 2016, Kim et

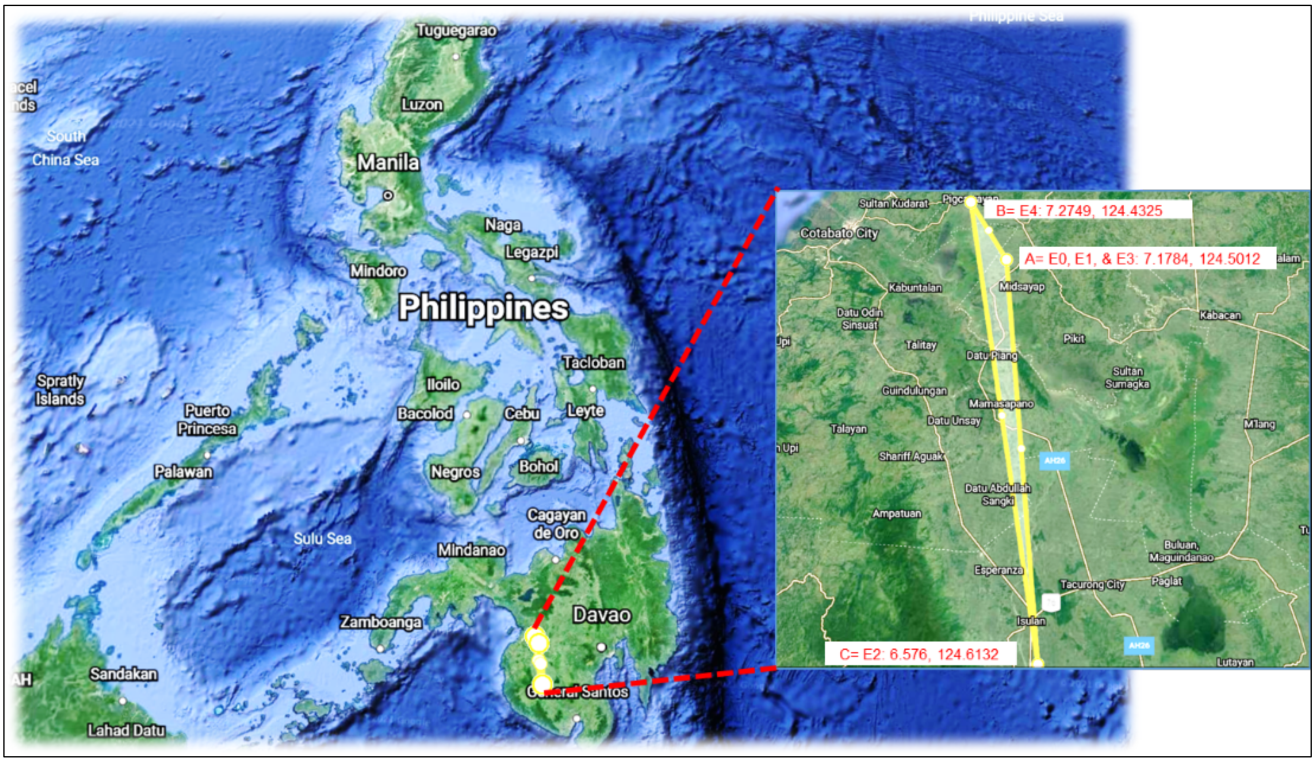

Figure 1: Location of the environment for the study and their corresponding global position system units. A is located at Midsayap, Cotabato, B is located at Pigcawayan, Cotabato, and C is located at Isulan, Sultan Kudarat.

Table 1: Grain yield performance of the 13 hybrid rice varieties in t/ha under E0 with normal condition and tested environments E1, E2, E3, and E4 with type IV climate condition.

Genotype	E0 (normal condition)	Tested environments				
		E1	E2	E3	E4	Mean
M1	10.05	10.81	8.33	6.33	4.46	7.48
M6	12.32	8.50	5.73	6.80	6.70	6.93
M12	6.62	5.07	6.02	5.90	3.60	5.15
M13	7.19	6.66	6.37	5.84	3.10	5.49
M20	6.71	5.71	5.98	5.25	3.62	5.14
M28	9.42	4.10	5.96	6.86	3.64	5.14
M32	8.43	5.67	4.90	4.75	4.58	4.98
M46	7.22	6.59	6.10	5.50	4.18	5.59
M51	8.12	4.80	6.35	6.40	3.82	5.34
M52	10.24	4.60	6.59	6.84	3.15	5.29
M55	7.41	9.29	7.93	5.92	4.29	6.86
M59	8.91	7.21	6.74	6.33	4.31	6.15
M60	10.96	9.81	8.19	6.90	4.70	7.4

E=environment, M=Mestizo

Table 2: Combined analysis of variance of the 13 hybrid rice varieties in four environments along with percentage of the known variance.

Source of variation	Df	Sum Sq	Mean Sq	F value	*p* value	Variance %
Location (E)	3	169.82	56.61	11.69	0.0027**	36.85
Replication (E)	8	38.75	4.84	2.68	0.0107*	8.41
Hybrid (G)	12	123.69	10.31	2.89	0.0069*	26.84
GXE	36	128.53	3.57	1.97	0.0047**	27.89
Residuals	96	173.81	1.81			

E=environment, G=genotype, * = significant at $p \leq 0.05$, ** = highly significant at $p \leq 0.005$

al., 2014, Peng et al., 2004, Xing et al., 2017), however, it may not be a factor in this study as the temperature for each tested environment was within the range from 27 to 32°C (Table 3), which is the normal range for rice to develop (Yin et al., 1996).

For the GxE effect, genotypic GY rankings varied across tested environment (Table 1). For instance, M1, M60, and M6 were the best performing genotypes to both E1 and E2, E3, and E4, respectively, while M28, M32, and M13 were the worst performing genotypes at E1, both E2 and E3, and E4, respectively. Of the genotypes, M6 was largely affected by the

Table 3: Meteorological data taken for each tested environment, E1 to E4, and the controlled environment, E0.

Variables		Type IV climate conditions				E0
		E1	E2	E3	E4	
Amount Rainfall (mm)	1st month	240	258	168	197	
	2nd month	208	392	145	268	
	3rd month	165	156	148	258	
	4th month	205	179	151	392	
	Average	204.5	246.25	153	278.75	
Solar radiation (W/m2)	1st month	213	159	210	210	213
	2nd month	210	152	203	190	210
	3rd month	213	177	190	159	213
	4th month	193	190	163	152	193
	Average	207.25	169.5	191.5	177.75	207.25
Average Temperature (°C)	1st month	28.85	29.1	27.85	30.1	28.85
	2nd month	28.65	27.9	28.05	29.6	28.65
	3rd month	28.05	28.5	28.05	29.1	28.05
	4th month	27.95	28.45	28.45	27.9	27.95
	Average	28.38	28.49	28.10	29.18	28.38

environment as it has the highest GY at E0 (normal condition) with 12.32 t/ha but having a 6.93 t/ha mean GY across tested environments. M6 had 5.39 t/ha GY difference between E0 and the average across tested environments, which was the largest GY deficit than any GY deficit of the other genotypes.

GGE biplot analysis

Using GGE biplots for GY had been done in several rice studies to determine which genotypes have broader adaptability or higher stability (Donoso-Ñanculao et al., 2016, Krishnamurthy et al., 2017, Mostafavi et al., 2011, Palanog et al., 2014). This study showed three GGE biplots with GGE biplot 1, the discriminative x representativeness with emphasis on the environment view (Figure 2), GGE biplot 2, the mean x stability with emphasis on the genotype view (Figure 3), and GGE biplot 3, the "which-won-where" with emphasis on the interaction patterns between genotypes and environments (Figure 4).

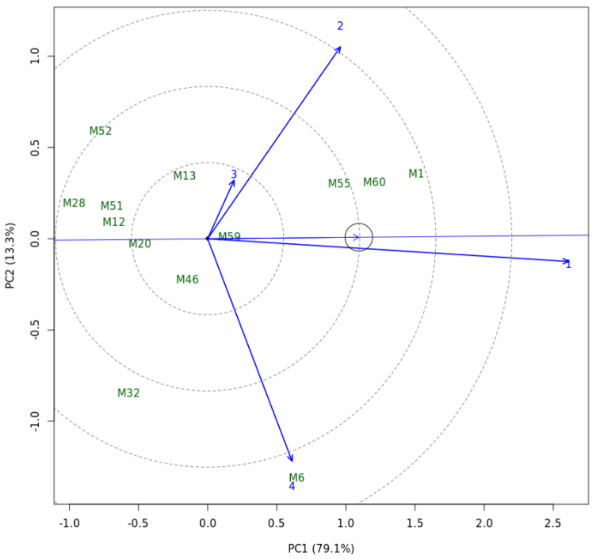

Figure 2: Genotype main effects and genotype x environment interaction (1) for the grain yield of 13 hybrid rice in four tested environments in discriminative x representativeness biplot representation. Number in blue fonts represents the tested environments while codes with a letter "M" and a number corresponds to the genotypes.

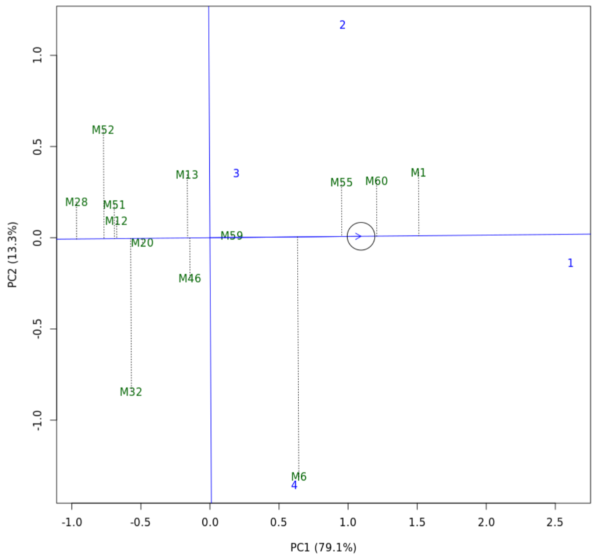

Figure 3: Genotype main effects and genotype x environment interaction (2) for the grain yield of 13 hybrid rice in four tested environments in mean x stability biplot representation. Number in blue fonts represents the tested environments while codes with a letter "M" and a number corresponds to the genotypes.

GGE biplot 1 showed the encircled arrow at the horizontal line which was the average environment axis (AEA) and four vectors pointing to each tested environment. The vector length represents the discriminating ability of an environment while the angle between an environment and the AEA represents the representativeness of an environment (Yan and Kang, 2003). With E1 having longest vector length and forming the smallest acute angle with the AEA, it was considered as the most discriminating environment and can represent other tested environments. Most of the genotypes were indeed performing better at E1 than in other tested environments.

In GGE biplot 2, the horizontal line had the AEA (encircled arrow) and the dashed lines of the genotypes while the vertical line represented the overall mean GY across tested environments. The dashed line of a genotype represents the stability of a genotype and if a genotype has a shorter dashed line or near to the horizontal line, it has a lesser GxE interaction and greater stability (Yan and Kang, 2003). Based on the figure, M59 and

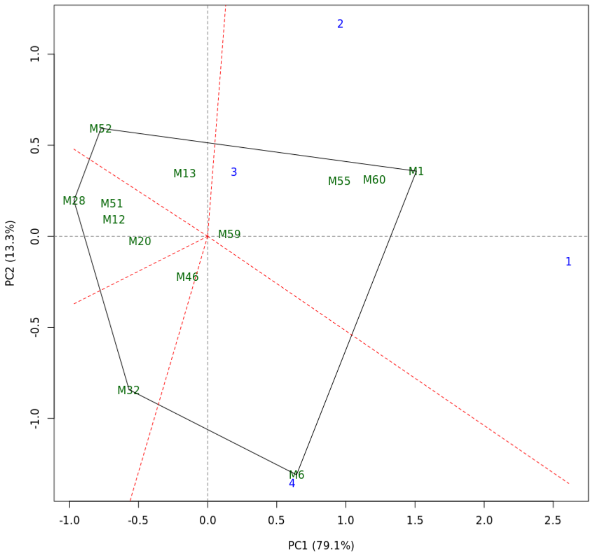

Figure 4: Genotype main effects and genotype x environment interaction (3) for the grain yield of 13 hybrid rice in four tested environments in which-won-where biplot representation. Number in blue fonts represents the tested environments while codes with a letter "M" and a number corresponds to the genotypes.

M20 were the most stable. However, M1, M60, and M55 were considered the best genotypes in terms of providing high and stable GY. Furthermore, M1, M60, and M55 were near to the horizontal line. M1 with 7.48 t/ha, M60 with 7.40 t/ha, and M55 with 6.86 t/ha mean GY across tested environments were the top 1, 2, and 4 highest mean GY, respectively, and thus the best performing genotypes.

GGE biplot 3 was used to determine top performing genotypes by visualizing the presence of crossover GxE and specific adaptation (Rakshit et al., 2012, Yan and Tinker, 2006). This study identified M1, M55, and M60 to be nearest with the E1 and so as M6 to E4, indicating these genotypes with specific adaptability. Consistent with the GY result, M1, M55, and M60 were the top 3 GY performing genotypes to both E1 and E2 and so as M6 to E4. For, M1 and M6, they also belong to the genotypes which enclosed a polygon view, implying these genotypes as the best GY performers for at least one tested environment (Krishnamurthy et al., 2017).

Ideal environment and hybrid rice varieties

E1 was identified as the ideal environment with type IV climate condition for hybrid rice. E1 was characterized with a normal temperature range (28.4°C), highest amount of solar radiation (207.25 W/m2), and intermediate amount of rainfall (204.5 mm) (Table 3). PhilRice MES, Midsayap, Cotabato or E1 is one of the NCT trial testing sites in the Philippines (Palanog et al., 2021). Furthermore, among the provinces in SOCCSARGEN region, Cotabato with 4.24 t/ha mean GY for five years (2010 to 2014) was higher than the 4.03 and 3.8 t/ha GY in South Cotabato and Sultan Kudarat, respectively (PSA, 2015).

For the genotypes, M1, M60, and M55 were considered not only for being stable but also having a high GY genotype across tested environments while M6 was considered due to its high GY and its specific adaptability at E4. For M1, it is a public-bred variety by International Rice Research Institute, which has an intermediate reaction response to rice blast, bacterial leaf blight and *Tungro* virus (PhilRice, 2021). Also, M1 was regarded as one of the best hybrids in the Philippines due to its soft eating quality/low amylose content (Frediles, 2018, PhilRice, 2021, Simeon, 2016). Another public-bred variety, M55 developed by PhilRice, has an intermediate reaction response to rice blast and a moderate resistance response to yellow stem borer (PhilRice, 2021). On the other hand, M60 is a private-bred variety. M60 has an intermediate reaction response to rice blast, bacterial leaf blight, and sheath blight (PhilRice, 2021). Lastly, M6 is also a private-bred variety and it has resistance response to rice blast (PhilRice, 2021). M6 was able to reach 15.45 t/ha in technology demonstration at Lumbao, Pampanga, Philippines and 16.63 t/ha in farmer's field at Guimba, Nueva Ecija, Philippines (BusinessMirror, 2016, Malabanan, 2019).

CONCLUSION

This study determined GxE interaction effect, stability of genotypes and representativeness and discriminating ability of an environment for GY. Though GY was highly affected by environment and GxE, hybrid rice varieties had a mean GY of 5.9 t/ha with its top 5 performing genotypes having ≥ 6.15 t/ha. Result in GY performance clearly showed that the hybrid rice varieties are good seed materials to be planted in type IV climate conditions.

GGE biplot model is an effective model which visualize the GxE interaction while identifying stable and high yielding genotypes. Among the 13 hybrid rice varieties, M1, M60, and M55 were the top performing in terms of providing high and stable GY. While M1, M60 and M55 were specifically best at E1 and E2, M6 was the only best genotype at E4, which was identified as most unideal for hybrid rice. Therefore, M1, M60, M6, and M55 are to be recommended for hybrid rice farming in environments with type IV climate condition.

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CONTRIBUTIONS OF INDIVIDUAL AUTHORS

AYC designed and proposed the study and drafted the manuscript. **IVB** collected the summarized the data while **AYC** did the statistical analyses. Both authors did the editing and revision of the manuscript.

CONFLICT OF INTEREST

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

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SUPPLEMENTARY DATA

Table S1: Descriptive statistics and normality test in each environment showing variability and normal distribution of the data.

Variables	E0	Tested Environments				Mean (E0-E4)	Mean (E1-E4)
		E1	E2	E3	E4		
Mean (t/ha)	8.74	6.83	6.55	6.12	4.17	6.48	5.92
Standard Error	0.34	0.42	0.28	0.19	0.17	0.17	0.26
Kurtosis	-0.81	0.46	-0.64	0.89	1.37	0.26	0.52
Skewness	0.29	0.72	0.56	-0.21	1.03	0.71	0.52
Range (t/ha)	8.04	11.38	6.11	5.91	5.03	11.48	7.11
Normality test value*	0.15	0.12	0.14	0.12	0.16	0.09	0.14

*significant if test value> alpha 0.05. E0= controlled environment.

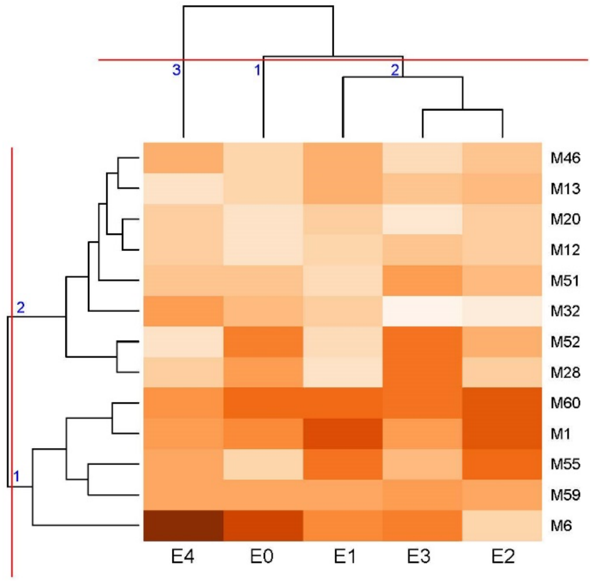

Figure S1: Genotype by environment interaction (GxE) heatmap showing relationship between 13 hybrid rice and across five environments.

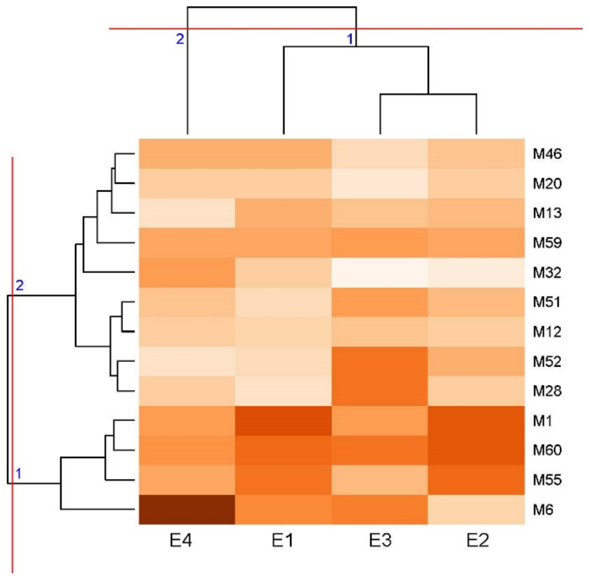

Figure S2: Genotype by environment interaction (GxE) heatmap showing relationship between 13 hybrid rice and across five environments.