Australian Journal of
Crop Science
AJCS

AJCS 16(04):512-521 (2022)
doi: 10.21475/ajcs.22.16.04.p3468
ISSN:1835-2707

Genotype × environment interaction and stability analysis on physicochemical traits of Malaysian rice hybrid across the environments

S. Elixon[1]*, Y. Mohd Rafii[2], R. Asfaliza[1], J. Mashitah[3], R. Shairul Izzan[3]

[1]Rice Research Centre, Malaysian Agriculture Research and Development Institute (MARDI), Malaysia
[2]Institute of Tropical Agriculture and Food Security, Universiti Putra Malaysia (UPM) Serdang, Malaysia
[3]Department of Crop Science, Faculty of Agriculture, Universiti Putra Malaysia (UPM), Serdang, Malaysia

***Corresponding author: elixons@mardi.gov.my**

Abstract

In the development of new varieties, physicochemical properties such as grain quality, milling, and chemical content are important. Twenty rice hybrids were tested in various environments in this study. Using multivariate and univariate models, the major goal is to identify rice hybrids with acceptable physicochemical properties and high stability. According to the ANOVA, variance due to season×genotype×location revealed a significant difference in length to width ratio, head rice recovery, and amylose content. Milled grain length and width varied from 6.64 to 7.32 mm and 1.78 to 2.06 mm, respectively, throughout the environments. The head rice recovery and amylose content, on the other hand, varied from 84.83 to 94.68% and 16.51 to 22.21%, respectively. The stability analysis for head rice trait using genotype superiority, static stability, Wrickie ecovelance, Nassar and Huehn, AMMI stability value, and coefficient of variation stability analysis, revealed that hybrids G2, G13, G8, G16, G7, G9, G6, G17, and G18 were the most stable. For Amylose content, hybrids G7, G4, G19, G10, G5, G17, G3, G12 and G11 were significantly stable. Except for G5, all hybrids demonstrated stable performance in the multivariate stability analysis for head rice recovery. Similarly, hybrids G3, G4, G5, and G7 responded in minimum GE interaction in multivariate analysis for amylose content. This discovery can help breeders pick potential hybrids by identifying the physicochemical attribute expression that was examined in different conditions.

Keyword: Physicochemical, hybrid rice, G × E interaction, genotype stability.

Abbreviations: AMMI_Additive main effect and multiplicative interaction, GGE_ Genotype main effects plus genotype × environment interaction, G×E_genotype by environment interaction, ANOVA_analysis of variance, PCV_phenotypic coefficient of variation, GCV_genotypic coefficient of variation, GL_grain length, GW_grain width, MGL_milled grain length, MGW_milled grain width, LW_length to width ratio, MR_milling recovery, HR_head rice recovery and AMY_amylose.

Introduction

The physicochemical features of grain quality, milling, and chemical content are significant traits to consider while selecting new varieties. Thus, quality improvement is always the primary goal in rice breeding that is aimed at consumer preferences (Caffagni, 2013). Although long and slender grain forms with a high percentage of milling recovery are profitable and can fetch a higher price, rice consumers are affected by eating and cooking characteristics (Bao, 2012; Rosniyana et al., 2006). Meanwhile, amylose content determines eating quality; high amylose rice has a higher volume expansion ratio, is dryer, less tender, and hardens when chilled; low amylose rice, on the other hand, is moist and sticky (Li et al., 2018).

The physicochemical properties are complicated traits, and it is inefficient to choose the optimum genotypes when tested across environments due to environmental impacts such as temperature, rainfall, and other factors. According to Shi et al.(2016), high night temperatures have been demonstrated to impair head rice recovery and grain width in rice genotypes. The chalkiness problem in rice grains was induced by environmental factors during the grain filling phase (Liu et al., 2010; Siebenmorgen et al. (2013). Amylose content, grain length, and width are among the genetically determined physicochemical characteristics that are less influenced by external influences (Fitzgerald et al., 2009). As a result, it is necessary to undertake a GE interaction analysis to determine genotype stability, either in general adaptability or maybe in specialised adaption (Balakrishnan et al. 2016). The genotype with the least sensitivity to environmental fluctuation is considered stable and most preferred in varietal selection (Jiban et al., 2020).

To characterise the performance of varieties in various environments and investigate the genotype and genotype by environment effect, an adequate stability analysis is required, which may guide rice breeders in selecting acceptable varieties. The ANOVA is commonly used to determine whether or not there is a GE interaction and to quantify the variance component of a random or fixed factor (Eder et al., 2014). To explore genotype stability in the context of the environment, parametric and non-parametric techniques are often used. Regression coefficient (Finlay and Wilkinson, 1963), static stability variance (Becker and Leon, 1988), Wricke's ecovalence (Wricke, 1962), coefficient of variability (Francis and Kannenberg, 1978), and superiority measure (Lin and Binns, 1988) are among parametric stability statistics, whereas Nassar and Huehn (1987), Kang (1988), and Fox et al (1990) are the non-parametrics. Multivariate stability approaches, on the other hand, are the most recent methodology employed in exploring and extracting patterns of GE interactions. Breeders' most widely used tools are the AMMI (additive main effects and multiplicative interaction) and GGE biplot (genotype main effect (G) and genotype by environment interaction (GE). These models are graphical depictions of interaction patterns that describe the interrelationships between components (genotypes, environments, and GE interactions), making it easier for the breeder to select stable and adaptable with broad adaptability or reaction in a given environment. As a result, the current study was conducted on 20 newly produced hybrids and two check varieties in four distinct locations and two planting seasons to analyse physicochemical traits as well as quantify the hybrid's performance and stability.

Results

Analysis of variance and variance components for physicochemical traits

Table 3 shows the pooled analysis of variance (ANOVA) for physicochemical properties across locations and seasons. All traits measured across locations showed highly significant differences. The GW, MGL, LW ratio, and HR did not differ significantly between the two planting seasons, whereas the MGL, MR, and HR did not differ significantly by genotype × location. The mean squares for season × genotype revealed no significant differences for all traits except LW, HR, and AMY content. The mean square for season × genotype × location revealed a significant difference in LW ratio, HR, and AMY, necessitating further statistical analysis to determine the genotype's stability across tested environments. In this study, only HR and AMY were examined for stability because these traits are important in determining grain quality and market demand. The estimation of variance components revealed that large differences were observed between σ^2_p and σ^2_g for MR, HR and AMY. The majority of the traits had a low GCV value (below 10). Meanwhile, intermediate PCV values were found in the LW ratio, MR, and AMY, while others were found to be low. In general, physicochemical heritability ranged from 23.98 to 51.60%. Except for LW ratio, which had a low value, all of the evaluated traits had medium broad-sense heritability.

Mean performance for physicochemical properties over environments

Table 4 shows the pooled mean for physicochemical properties across the environment. The value for the GL trait ranged from 9.46 to 10.30 mm, and the majority of the hybrids showed no significant difference among them. Hybrids G11, G17, G14, G16, G1, G6, G3, G5, G6, G12, and G2 were not statistically different from the control varieties. In comparison, hybrids G8, G7, G18, G19, G15, G20, G9, G10, and G12 had lower GL values than the control varieties. For the GW, hybrid G6 had the highest mean, followed by G20, G4, and G2, while hybrids G1, G8, G15, and G16 had the lowest. The mean values for MGL ranged from 6.64 to 7.32 mm, with hybrids G6, G20, and G3 having a significant and higher MGL value than the check varieties, while G15 and G18 had the lowest mean. The mean values for MGW ranged from 1.78 to 2.06 mm, with G1, G8, G9, and G10 having the lowest mean, which was not significantly different from the check varieties G21 and G22. In contrast, hybrids G6, G20, G11, and G4 had significantly higher MGW than the control varieties. For the L/W ratio, the mean value ranged from 3.56 to 3.89 mm, with no significant differences observed for the majority of the hybrids. Meanwhile, the average MR trait value ranged from 57.84 to 72.68 %. G20, G7, and G8 hybrids produced a high mean MR (above 65%). In contrast, hybrid G1 produced the least amount of MR, even less than the check varieties G21 and G22. All genotypes had satisfactory HR mean values, with yields ranging from 84.83 to 94.68 %. The hybrid G18 had the highest mean for HR, followed by G20, G6, G7, and G8, and the hybrid G19, G5, G1, and G14 had the lowest value. The mean amylose (AMY) content ranged from 16.51 to 22.21 % across environments. Hybrids G2, G3, G4, G5, G7, G9, G18, and check variety G21 had AMY content greater than 20%, while other hybrids had AMY content less than 20%.

Univariate stability analyses for head rice recovery and amylose content

The univariate analyses (Table 5) explain that hybrids with lower stability scores performed stable which contrarily those hybrids recorded large scores. Lin and Binn analysis defined that hybrids G18, G7, G8, G6, G20, G9, G16, and G13 were the most superior hybrids because they had low P_i scores. The S^2 analysis ranked hybrids G2, G8, G15, G7, G13, G18, G16, and G10 in terms of stability performance, whereas the W_i analysis revealed that hybrids G2, G13, G8, G16, G17, G4, G7, and G14 had small scores, indicating a stable performance for HR production. The Nassar and Huehn analysis found that hybrids G8, G13, G16, G6, G7, and G18 had less genotype by environment interaction due to low scores. AMMI stability value (ASV) scores for hybrids G7, G8, G16, G13, G6 and G18 were low. Meanwhile, the CV_i stability analysis revealed that the stable hybrids were classified as G8, G9, G2, G7, G3, G13, and G16. Overall rank stability revealed that G8 hybrids were the most stable, followed by G2, G13, G7 and G16.

Meanwhile, Lin and Binn's analysis of AMY content revealed that G7, G4, G9, G5, and G18 had low P_i scores, indicating that they performed well. According to S^2 scores, hybrids G10, G17, G19, G4, and G7 were the most stable, while hybrids G8, G9, G14, G1, and G18 were the least stable. The W_i stability analysis showed that hybrids G19, G10, G7, G17, G4, and G5 were the most stable when compared to hybrids G8, G18, G1, G2, and G9. The non-parametric Nassar and Huehn stability analysis revealed that hybrids G7, G19, G4, G5, and G6 had lower values for $Si^{(1)}$ and $Si^{(2)}$ indicating less G×E influences for AMY than hybrids G8, G1, G2, G21, and G13. The ASV stability for amylose revealed that hybrids G19, G10, G12, G4, G17, G6, and G7 had low stability scores, indicating that they were less influenced by the environment. The CVi stability analysis revealed that hybrids with stable performance were found in G1, G17, G4, G19, G11, G3, and G5, while unstable hybrids were found in G8, G14, G20, G1, G9, and G6. The overall rank stability for AMY concludes that hybrids G7, G4, G19, G10, and G5 were the most stable, with a small total score, while unstable hybrids were found in hybrids G8, G1, G2, G9, and G18.

AMMI stability analyses

The AMMI 1 biplot explains the primary effects of genotype and environment in AMMI analysis models, and then the IPCA1 values for both genotypes and environments are displayed against each other. IPCA1 is used to illustrate the AMMI 2 biplot, while IPCA2 is used to explain the genotype and environment in a more specific interaction. In the AMMI 1 biplot, differences in main (additive) effects are indicated by genotype/environment displacements along the abscissa, while differences in interaction effects are indicated by genotype/environment displacements along the ordinate. A genotype or environment with an IPCA1 score closer to zero, on the other hand, implies modest interaction effects and performs consistently. The environmental or genotype scores in the AMMI 2 biplot are connected to the biplot origin, which explains why genotypes or environments with short spokes have less interaction than those with long spokes.

In Figure 1A, the AMMI1 biplot for HR revealed that IPCA1 accounted for 31.36% of the sum square variation. The AMMI 1 biplot of mean versus IPCA1 revealed that hybrids G18, G20, G6, G7, G8, and G9 had IPCA1 values closer to zero, indicating less environmental interaction and also being desirable for high HR values. In AMMI2 biplot, the first two IPCAs accounted about 51.12% of the overall variation in HR production (Figure 1B). As seen closer to the biplot origin, the majority of the hybrids performed consistently. The presence of environmental influences is indicated by hybrids G5 and G20 with longer spokes from biplot origin. Hybrid G5 demonstrated a specific interaction with AR1 and BM2, whereas G20 adapted better to BR1.

The AMMI1 biplot for AMY indicates that the IPCA 1 had 40.37% of the total sum variation. The AMMI biplot for mean vs IPCA1 revealed that among the evaluated hybrids, G7, G4, G21, G22, G17, G10, G19, G20, G12, and G16 showed closer to zero, indicating less GE interaction (Figure 2A), whereas hybrids G18, G2, G9, G3, G11, and G5 had large IPCA1 scores and were farthest from the biplot centre, indicating greater GE interaction. The GE interactions in the AMMI 2 biplot revealed that the portioned of the first two principal components contributed for 61.80% of the total variation. The AMMI2 of IPCA1×IPCA2 (Figure 2B) found that hybrids G7, G3, G4, and G5 were closer to the biplot centre, indicating a minimal environmental effect and a stable genotype. Similarily, hybrids G10, G6, G19, and G12 closer to the biplot centre and performed consistently across environments.

GGE biplot stability analyses

The polygon view of the which-won-where pattern explains which genotypes performed better in one or more environments. The winning variety is defined as the best performing genotypes or known as a vertex in specific environments that formed the polygon. The polygon view for HR in Figure 3A revealed that the G+GE contributed approximately 66.21 percent of total variation with the vertex genotypes being hybrids G18, G20, G19, and G5. Vertex G18 and G20 were discovered to be winning varieties in mega environments including such BM1, BM2, TC1, TC2, AR1, and BR2. Other hybrids, such as the G6, G7, G8, and G16, were also found to be suitable in these environments. Meanwhile, hybrids G6 and check varieties G21 and G22 were relevant in sectors represented by environments BR1 and AR2. The stable hybrids were near the AEC abscissa, and the arrow pointed in the direction of better performance (Figure 3B). As a result, the hybrids on the right side of the figures and near the AEC (average environment coordinate) abscissa line had the best performance and stability. As a result, hybrids G20, G8, G7, G18, and G9 with short AEC spokes performed well in terms of stability and desirable mean HR value. The most unstable performance was found in the Hybrid G5, which had longer AEC spokes and a lower mean HR value.

The GGE biplot in which-won-where pattern (Figure 4A) captured 77.92% of the G+GE total variation for AMY content. The GGE biplot revealed that the vertex genotypes that formed the polygon into sectors were hybrids G7, G18, G8, G6, G20, G1, and G9. The vertex genotype for environments BM2 and TC2 was observed in hybrid G7, the vertex genotype for environments BR1, BR2, and AR2 was observed in hybrid G18, and the vertex genotype for environments BM1 and BR1 was observed in hybrid G9. The GGE biplot for mean vs stability for AMY content revealed that hybrids G7 and G18 had the highest AMY content, followed by hybrids G9, G3, G4, and G5, while hybrids G20, G6, G19, and G12 had the lowest AMY content (Figure 4B). In terms of stability, hybrids G7 and G7 performed consistently across the environment, connecting shorter spokes from the AEC line and, contrarily, hybrids with longer spokes. As seen farthest away from the AEC line, hybrid G18 demonstrated strong environmental interaction. Despite having higher mean AMY levels, hybrid G9 and G3 showed similar inconsistencies in stability.

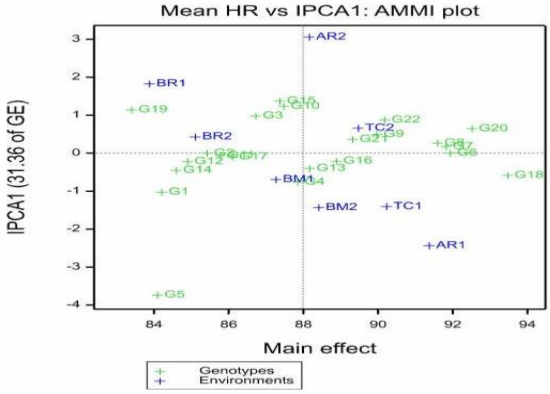
Discussion

The pooled analysis of variance indicated that genotypes differed for all physicochemical traits indicating that genotype variability is sufficient for selecting genotypes with desired characteristics. In this study, there was a variation in physicochemical traits due to location, showing that the investigated locations were diverse. The expression of the GW, MGL and HR traits is unaffected by season, whereas the GL, GW, MGL, MGW, and MR traits are unaffected by genotypes × season and genotypes × environment interaction, indicating that genotypes respond equally across environments. The occurrence of a significant in genotype × environment for the L/W ratio, HR, and AMY traits suggests that environmental variation influences their expression. The amylose showed highly interacts with cropping seasons, this finding was in agreement with Kitara et al. (2019). As a result, stability assessments must be conducted to assist breeders in genotype selection that is either stable across environments or specific adaption as explained by Demelash et al. (2019).

In general, the GL, GW, MGL, MGW and LW ratio had a low phenotypic coefficient of variation (PCV) and genotypic coefficient of variation (GCV) values indicating that there is

Table 1. List of rice genotypes used in the study.

Entry	Type	Pedigree	Entry	Types	Pedigree
G1	Hybrid	IR79126A/6165R	G12	Hybrid	0047A/6161R
G2	Hybrid	IR70369A/6161R	G13	Hybrid	0025A/6594R
G3	Hybrid	0047A/P584	G14	Hybrid	0047A/6187
G4	Hybrid	IR70369A/6559R	G15	Hybrid	0047A/MR152
G5	Hybrid	IR70369A/ENT42	G16	Hybrid	0047A/6301R
G6	Hybrid	IR70369A/ENT19	G17	Hybrid	0025A/6149R
G7	Hybrid	IR70369A/YBL537	G18	Hybrid	0047A/YBL537
G8	Hybrid	0047A/E54	G19	Hybrid	0047A/6289
G9	Hybrid	0025A/MRQ97	G20	Hybrid	0025A/ENT19
G10	Hybrid	0025A/6117R	G21	Inbred (MR263)	-
G11	Hybrid	IR70369A/6296R	G22	Inbred (MR269)	-



Mean genotypes and environments for head rice trait

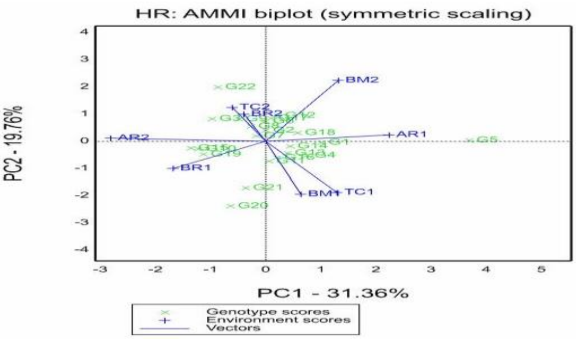


Figure 1. AMMI biplot of A) stability mean head rice *vs* IPCA1 and B) IPCA1 *vs* IPCA2 effect of both genotypes and environments on 22 rice genotypes in eight environments for head rice recovery.

Table 2. Description of the locations in two cropping seasons.

Env	Coordinates	Seasons	Average Temp. (Min – Max) (° C)	Rainfall monthly mean (mm)	Av. Humidity (%)	Soil texture	CEC (meq/100
BM1	5°24'42.0"N 100°25'54.2"E	MS	22.5 – 34.1	123.1 – 453.4	83.9 – 86.5	Sandy Clay Loam	21.64 – 35.2
BM2	5°24'42.0"N 100°25'54.2"E	OS	22.4 – 34.6	98.2 - 437.7	80.2 – 84.3		
TC1	6°05'43.8"N 100°19'52.7"E	MS	21.5 – 35.9	69.2 – 309.3	76.4 – 90.0	Silty clay	30.63 – 33.7
TC2	6°05'43.8"N 100°19'52.7"E	OS	21.7 – 34.3	100.3 – 473.3	84.6 – 86.6		
BR1	5°32'31.4"N 100°28'09.0"E	MS	22.5 – 34.1	123.1 – 453.4	83.9 – 86.5	Silt Loam	12.6 – 13.8
BR2	5°32'31.4"N 100°28'09.0"E	OS	22.4 – 34.6	98.2 - 437.7	80.2 – 84.3		
AR1	6°23'05.3"N 100°14'47.4"E	MS	21.9 – 37.5	7.8 - 228.6	83.7 – 87.0	Clay	30.4 – 30.8
AR2	6°23'05.3"N 100°14'47.4"E	OS	22.4 – 36.0	128.8 - 479.2	82.8 – 84.0		

Notes: Env = environment, MS = main season (November 2017 – March 2018), OS = off season (April 2017 – September 2017), BM = Bukit Merah Penang, TC = Telok Chengai, Kedah, BR = MARDI Bertam Penang and AR = MARDI Arau Perlis.

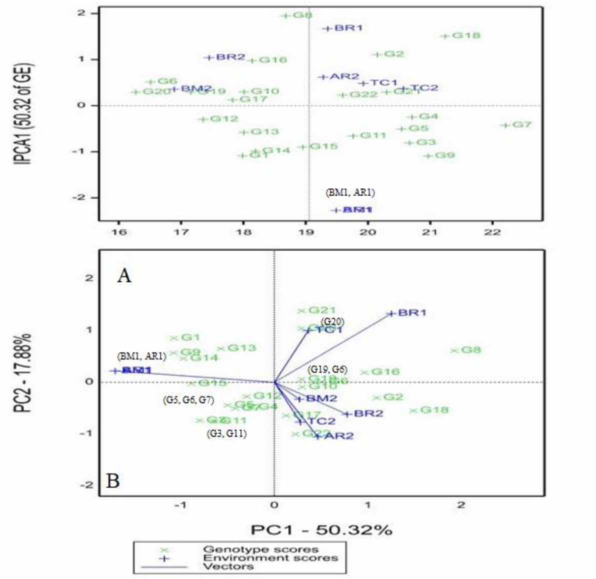


Figure 2. AMMI1 biplot A) stability mean amylose *vs* IPCA1 and B) AMMI2 for IPCA1 *vs* IPCA2 effect of both genotypes and environments on 22 rice genotypes in eight environments for amylose content.

Table 3. ANOVA, genetic variances and heritability values for physicochemical properties across locations and seasons.

Source	DF	GL	GW	MGL	MGW	LW	MR	HR	AMY
Location (L)	3	1.26^{**}	1.52^{**}	2.27^{**}	0.06^{**}	4.79^{**}	156.22^{**}	828.40^{**}	118.93^{**}
Rep in L and S	16	0.289^{**}	1.19^{**}	0.11^{*}	0.21^{**}	0.31^{**}	290.99^{**}	21.31^{ns}	34.03^{**}
Season (S)	1	1.43^{**}	0.08^{ns}	0.12^{ns}	0.70^{**}	0.04^{ns}	2617.05^{**}	21.28^{ns}	136.23^{**}
S×L	3	0.02^{**}	0.22^{**}	3.03^{**}	0.05^{**}	1.48^{**}	215.09^{**}	221.76^{**}	73.67^{**}
Genotypes (G)	21	1.13^{**}	0.26^{**}	0.80^{**}	0.11^{**}	0.19^{**}	144.92^{**}	144.09^{**}	64.81^{**}
G×L	63	0.16^{**}	0.06^{**}	0.11^{**}	0.01^{ns}	0.07^{*}	28.18^{ns}	28.69^{ns}	9.10^{**}
G×S	21	0.05^{ns}	0.01^{ns}	0.07^{ns}	0.01^{ns}	0.10^{**}	44.28^{ns}	52.52^{**}	15.15^{**}
G×L×S	63	0.03^{ns}	0.02^{ns}	0.07^{ns}	0.01^{ns}	0.06^{*}	21.38^{ns}	39.50^{**}	7.42^{**}
Error	336	0.09	0.03	0.06	0.01	0.04	31.63	22.63	3.86
σ^2_g		0.04	0.01	0.03	0.00	0.00	6.83	7.50	2.00
σ^2_{gl}		0.02	0.01	0.01	0.00	0.00	1.13	0.00	0.28
σ^2_{gs}		0.00	0.00	0.00	0.00	0.00	1.91	1.09	0.64
σ^2_{gls}		0.00	0.00	0.00	0.00	0.01	0.00	5.62	1.18
σ^2_p		0.15	0.05	0.10	0.02	0.06	41.51	36.84	7.97
σ^2_e		0.09	0.03	0.06	0.01	0.04	31.63	22.63	3.86
GCV (%)		1.98	4.10	2.46	3.50	1.54	4.15	3.11	7.42
PCV (%)		3.90	9.43	4.47	6.78	6.43	10.24	6.90	14.81
h^2_B (%)		50.76	43.49	54.96	51.60	23.98	40.58	45.13	50.09

Notes: GL = grain length, GW = grain width, MGL = milled grain length, MGW = milled grain width, LW = length to width ratio, MR = percentage of milling recovery, HR = percentage of head rice recovery, AMY = amylose, σ^2_g = Genotypic variance, σ^2_p = Phenotypic variance, σ^2_e = Error variance, PCV = Phenotypic coefficient of variation, GCV = Genotypic coefficient of variation and h^2_B = Broad sense heritability, **highly significant at $P \le 0.01$ probability levels and *significant at $P \le 0.05$ probability levels and ns = not significant

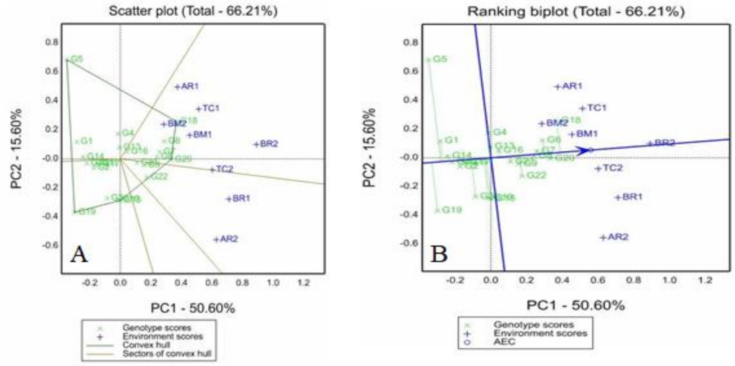


Figure 3. GGE biplot of 22 rice genotypes on A) polygon view which-won-where pattern and B) ranking genotypes *vs* stability for head rice trait in eight tested environments.

Table 4. Mean performances of rice genotypes for physico-chemicals properties over mega environment.

Gen	GL (mm)	GW (mm)	MGL (mm)	MGW (mm)	LW ratio	MR (%)	HR (%)	AMY (%)
G1	10.19 ± 0.05^{a-d}	2.17 ± 0.03^{j}	6.75 ± 0.10^{e-h}	1.79 ± 0.02^{fgh}	3.78 ± 0.09^{a-e}	57.84 ± 2.29^{g}	84.21 ± 1.76^{ij}	17.99 ± 0.91^{d-i}
G2	10.30 ± 0.22^{a}	2.33 ± 0.06^{cd}	6.93 ± 0.08^{cd}	1.88 ± 0.02^{b-e}	3.69 ± 0.07^{b-f}	60.08 ± 2.76^{fg}	85.43 ± 0.84^{g-j}	20.15 ± 0.80^{a-e}
G3	10.24 ± 0.09^{ab}	2.28 ± 0.04^{de}	7.09 ± 0.06^{b}	1.87 ± 0.03^{b-e}	3.82 ± 0.08^{abc}	60.59 ± 1.58^{efg}	86.72 ± 1.30^{e-j}	20.67 ± 0.65^{abc}
G4	10.09 ± 0.15^{def}	2.42 ± 0.05^{b}	6.91 ± 0.08^{cde}	1.91 ± 0.04^{bc}	3.63 ± 0.09^{c-f}	62.88 ± 1.98^{b-f}	87.84 ± 1.25^{i}	20.71 ± 0.51^{abc}
G5	10.27 ± 0.06^{ab}	2.33 ± 0.05^{cd}	6.88 ± 0.06^{cde}	1.88 ± 0.04^{b-e}	3.67 ± 0.08^{b-f}	64.28 ± 1.81^{b-f}	84.10 ± 3.09^{ij}	20.54 ± 0.72^{abc}
G6	10.27 ± 0.24^{ab}	2.45 ± 0.06^{b}	7.36 ± 0.10^{a}	2.06 ± 0.05^{a}	3.60 ± 0.10^{ef}	60.71 ± 4.48^{d-g}	91.94 ± 1.42^{abc}	16.51 ± 0.79^{hi}
G7	9.70 ± 0.14^{j}	2.56 ± 0.12^{a}	6.69 ± 0.08^{gh}	1.90 ± 0.05^{bcd}	3.56 ± 0.09^{f}	66.70 ± 1.91^{b}	91.83 ± 1.09^{abc}	22.21 ± 0.55^{a}
G8	9.46 ± 0.07^{k}	2.20 ± 0.04^{g-j}	6.72 ± 0.08^{fg}	1.79 ± 0.03^{gh}	3.78 ± 0.08^{a-e}	65.09 ± 1.19^{bc}	91.59 ± 0.93^{a-d}	18.68 ± 2.24^{c-h}
G9	10.00 ± 0.11^{fgh}	2.17 ± 0.03^{j}	6.82 ± 0.09^{c-g}	1.83 ± 0.04^{e-h}	3.76 ± 0.11^{a-e}	62.58 ± 1.41^{c-f}	89.96 ± 1.40^{a-f}	20.97 ± 1.02^{abc}
G10	10.02 ± 0.06^{efg}	2.29 ± 0.02^{de}	6.88 ± 0.10^{cde}	1.84 ± 0.03^{d-h}	3.76 ± 0.08^{a-e}	63.80 ± 1.13^{b-f}	87.47 ± 1.21^{e-j}	18.01 ± 0.23^{d-i}
G11	10.09 ± 0.38^{c-f}	2.29 ± 0.02^{de}	6.87 ± 0.08^{c-f}	1.93 ± 0.05^{b}	3.59 ± 0.09^{ef}	64.30 ± 1.29^{b-e}	85.78 ± 1.61^{f-j}	19.76 ± 0.60^{b-e}
G12	10.28 ± 0.08^{a}	2.23 ± 0.03^{f-i}	6.97 ± 0.10^{bcd}	1.86 ± 0.03^{b-e}	3.75 ± 0.05^{a-e}	61.81 ± 2.12^{c-g}	84.90 ± 1.76^{hij}	17.35 ± 0.76^{f-i}
G13	10.06 ± 0.16^{d-g}	2.27 ± 0.03^{ef}	7.00 ± 0.10^{bc}	1.87 ± 0.03^{b-e}	3.77 ± 0.08^{a-e}	60.87 ± 1.91^{d-g}	88.17 ± 1.12^{b-i}	18.01 ± 0.76^{d-i}
G14	10.19 ± 0.08^{a-d}	2.35 ± 0.05^{c}	6.94 ± 0.10^{bcd}	1.86 ± 0.04^{b-f}	3.75 ± 0.06^{a-e}	60.79 ± 1.56^{d-g}	84.59 ± 1.68^{hij}	18.20 ± 0.95^{d-i}
G15	9.87 ± 0.08^{hi}	2.19 ± 0.01^{ij}	6.63 ± 0.07^{h}	1.82 ± 0.04^{e-h}	3.66 ± 0.09^{b-f}	61.75 ± 3.15^{c-g}	87.37 ± 1.09^{e-j}	18.95 ± 0.82^{b-g}
G16	10.19 ± 0.11^{a-d}	2.19 ± 0.03^{hij}	6.88 ± 0.10^{cde}	1.82 ± 0.03^{e-h}	3.80 ± 0.08^{a-d}	60.22 ± 2.14^{fg}	88.88 ± 1.16^{b-h}	18.14 ± 0.73^{d-i}
G17	10.14 ± 0.11^{b-e}	2.29 ± 0.03^{de}	6.95 ± 0.08^{bcd}	1.88 ± 0.05^{b-e}	3.72 ± 0.08^{a-f}	61.89 ± 1.73^{c-f}	86.10 ± 1.37^{e-j}	17.83 ± 0.36^{e-i}
G18	9.77 ± 0.10^{ij}	2.37 ± 0.04^{c}	6.64 ± 0.09^{h}	1.85 ± 0.05^{c-g}	3.60 ± 0.10^{def}	64.28 ± 2.58^{b-e}	93.46 ± 1.15^{a}	21.24 ± 0.86^{ab}
G19	9.94 ±0.10^{gh}	2.24 ± 0.04^{e-h}	6.88 ± 0.11^{cde}	1.87 ± 0.05^{b-e}	3.71 ± 0.13^{a-f}	64.65 ± 1.72^{bcd}	83.40 ± 1.63^{j}	17.15 ± 0.45^{ghi}
G20	9.97 ± 0.07^{fgh}	2.43 ± 0.04^{b}	7.32 ± 0.08^{a}	2.01 ± 0.04^{a}	3.66 ± 0.09^{b-f}	72.68 ± 1.49^{a}	92.52 ± 1.96^{ab}	16.27 ± 0.85^{i}
G21	10.27 ± 0.06^{ab}	2.17 ±0.06 ^{j}	6.88 ± 0.08^{cde}	1.78 ± 0.04^{h}	3.89 ± 0.11^{a}	63.01 ± 0.94^{b-f}	89.33 ± 1.18^{ab}	20.30 ± 0.71^{a-d}
G22	10.22 ± 0.06^{abc}	2.25 ± 0.08^{efg}	6.82 ± 0.11^{d-h}	1.78 ± 0.03^{h}	3.84 ± 0.08^{ab}	63.69 ± 1.98^{b-f}	90.17 ± 1.47^{a-e}	19.60 ± 0.65^{b-f}
Mean	10.07	2.29	6.90	1.87	3.72	62.93	87.99	19.06
CV (%)	3.00	7.76	3.43	4.86	5.62	3.99	5.41	10.31
LSD$^{0.05}$	0.13	0.05	0.16	0.17	0.34	8.94	4.35	2.34

Notes: Means within the same column having the same superscript are not statistically different at P≤0.05 based on Least Significant Different (LSD). GL = grain length, GW = grain width, MGL = milled grain length, MGW = milled grain width, LW = length to width ratio, MR = percentage of milling recovery, HR = percentage of head rice recovery, AMY = amylose and GC = gel consistency.

Table 5. Mean, stability ranking and overall ranking of rice genotypes for head rice recovery and amylose content.

Trt	Gen	Mean	R	P_i	R	S^2	R	W_i	R	$Si^{(1)}$	R	$Si^{(2)}$	R	ASV	R	CV_i	R	TS	OR
Head rice recover (%)	G1	84.21	20	71.93	20	24.68	19	64.34	11	5.000	12	21.71	11.5	1.29	14	7.48	21	108.5	16
	G2	85.42	17	53.5	16	5.54	1	10.86	1	2.786	2	5.43	2	0.40	2	3.26	5	29	2
	G3	86.73	14	47.37	14	13.51	11	100.36	17	6.821	19	31.7	18	1.49	15	3.58	7	101	14
	G4	87.85	11	32.67	11	12.45	10	36.49	6	6.179	16	26.41	16	1.10	13	5.08	15	87	9
	G5	84.09	21	91.08	22	76.63	22	355.81	22	8.357	22	50	22	4.71	22	11.49	22	154	20
	G6	91.93	3	11.83	4	16.16	14	61.79	10	4.036	8	11.41	8	0.74	7	4.72	13	64	6.5
	G7	91.82	4	9.53	2	9.45	4	38.06	7	4.107	9	12.55	9	0.29	1	3.54	6	38	4
	G8	91.59	5	10.68	3	6.95	2	14.7	3	2.714	1	5.14	1	0.65	4	2.52	2	16	1
	G9	89.96	7	22.26	6	15.82	13	59.07	9	5.571	14	24.79	14	1.03	12	2.99	4	72	8.5
	G10	87.48	12	39.49	13	11.8	9	97.17	16	4.857	11	21.71	11.5	1.58	17	4.47	12	89.5	10
	G11	85.77	16	55.71	17	20.58	16	132.4	20	5.679	15	22.41	13	0.75	8	5.95	20	109	17
	G12	84.9	18	65.14	18	24.83	20	75.7	13	3.821	7	10.12	6	0.99	11	5.94	19	94	13
	G13	88.17	10	29.61	10	9.97	5	13.28	2	3.214	3	7.36	3	0.67	6	3.59	8	37	3
	G14	84.6	19	66.41	19	22.46	18	39.38	8	3.357	4	7.93	4	0.60	3	5.48	16	72	8.5
	G15	87.37	13	38.74	12	9.44	3	76.74	14	6.250	17	26.7	17	1.75	18	3.78	10	91	11
	G16	88.88	9	24.84	9	10.85	7	14.85	4	3.714	6	10.21	7	0.66	5	3.74	9	47	5
	G17	86.09	15	49.81	15	14.98	12	31.89	5	3.464	5	8.84	5	0.86	10	4.90	14	66	7
	G18	93.47	1	6.12	1	10.56	6	69.02	12	4.357	10	26.29	15	0.80	9	3.99	11	64	6.5
	G19	83.4	22	83.88	21	21.25	17	123.32	19	5.071	13	20.5	10	1.52	16	5.84	17	113	18
	G20	92.52	2	14.08	5	30.73	21	174.33	21	6.321	18	44.7	20	2.54	21	5.92	18	124	19
	G21	89.32	8	23.92	7	11.23	8	93.72	15	8.071	21	45.36	21	1.80	19	1.21	1	92	12
	G22	90.17	6	24.17	8	17.19	15	116.01	18	7.107	20	43.55	19	2.29	20	2.69	3	103	15
Amylose content (%)	G1	17.99	16	16.29	17	6.69	19	30.36	20	6.84	21	32.28	19	2.01	20	14.38	19	135	21
	G2	20.15	8	7.71	8	5.08	15	30.29	19	6.43	20	29.43	18	1.88	18	11.19	11	109	20
	G3	20.67	5	4.52	4	3.38	7	21.8	15	4.64	7	16.00	6	1.55	15	8.90	7	61	7
	G4	20.71	4	3.86	2	2.08	4	10.23	5	2.79	3	5.36	3	0.64	4	6.97	3	24	2
	G5	20.54	6	4.52	4	4.13	10	11.62	6	3.38	4	8.50	4	0.96	8	9.90	10	46	5
	G6	16.51	20	25.45	20	4.97	14	15.75	11	4.43	5	20.21	9	0.86	6	13.50	17	82	11
	G7	22.21	1	1.19	1	2.42	5	7.36	3	1.86	1	3.71	1	0.88	7	7.00	4	22	1
	G8	18.68	12	15.63	15	10.41	22	62.56	22	8.61	22	53.27	21	3.33	22	17.27	22	146	22
	G9	20.97	3	4.11	3	8.32	21	29.93	18	5.79	15	23.43	13	1.92	19	13.76	18	107	19
	G10	18.01	15	14.62	11	0.43	1	5.3	2	4.86	9	16.57	8	0.51	2	3.63	1	34	4
	G11	19.76	9	7.05	7	2.86	6	13.5	7	6.00	16	32.29	20	1.35	12	8.56	6	74	10
	G12	17.35	18	19.62	19	4.62	12	14.87	9	4.48	6	13.82	5	0.58	3	12.38	16	70	9
	G13	18.01	15	15.7	16	4.68	13	15.37	10	6.38	18	28.92	17	1.17	11	12.01	14	99	15
	G14	18.20	13	14.68	12	7.29	20	20.74	14	5.43	12	20.21	9	1.72	17	14.84	21	105	17
	G15	18.95	11	10.63	10	5.39	16	16.69	12	5.61	13	22.84	12	1.50	14	12.24	15	92	13
	G16	18.14	14	15.34	13	4.21	11	19.6	13	6.14	17	26.00	15	1.65	16	11.32	12	97	14
	G17	17.83	17	15.56	14	1.06	2	9.67	4	5.32	11	22.27	11	0.68	5	5.77	2	49	6
	G18	21.24	2	5.27	5	5.86	18	43.92	21	5.68	14	25.41	14	2.59	21	11.39	13	106	18
	G19	17.15	19	19.42	18	1.65	3	2.4	1	2.21	2	4.00	2	0.50	1	7.48	5	32	3
	G20	16.27	21	26.94	21	5.77	17	28.78	17	4.71	8	16.50	7	1.16	10	14.75	20	100	16
	G21	20.30	7	6.34	6	3.99	9	28.06	16	6.39	19	28.48	16	1.48	13	9.84	9	88	12
	G22	19.60	10	8.33	9	3.40	8	13.97	8	5.25	10	20.84	10	1.08	9	9.41	8	62	8

Notes: Trt = trait, R = Rank, Pi = lin and Binn, S^2 = static stability, W_i=Wrickie ecovelance, Si $^{(1)}$ and Si$^{(2)}$ = Nassar and Huehn, ASV = AMMI Stability Value and CV_i = Francis and Kannenberg, TS = total score and OR = overall rank.

limited scope for improvement and large size of population selection with a broad genetic base is required for further improvement. Low PCV and GCV for MGL were contradicted with Bharat et al. (2018) and Richa et al. (2019) reported moderate and high PCV and GCV in milled grain length and milled grain width traits, which could be related to changes in environmental conditions between Malaysia and their environment. Except for the L/W ratio, the GL, GW, MGL, and MGW were less sensitive to the environment, as seen by the small gap value of PCV and GCV. Grain properties; GL, GW, MGL and MGW are important traits that need to be considered in the breeding of preferable grain quality of new hybrid rice varieties. The GL and GW traits are important in the early selection of grain properties which later dehusked and measured its MGL and MGW properties. The MGL is characterised as long (above 6.2 mm), medium (5.20 – 6.19 mm), or short (below 5.5 mm) grain based on the largest dimension in length. Long (>6.21mm MGL) and slender grain (>3.0 mm L/W ratio) is preferred by Malaysian consumers and can fetch a higher price than medium or short grains (Rosniyana et al., 2006). To that purpose, all of the hybrids tested met the requirements of local customers.

Overall, the percentage of head rice recovery was sufficient in production. Base on the laboratory scale, the acceptable milling and head rice recovery are range from 68% to 72% and 50 to 58%, respectively (IRRI, 2020), whereas for commercial view head rice recovery around 55 to 60% considered sufficient (Marie et al., 2019). The PCV value recorded doubled than the GCV for MR and HR traits indicating some degree of environmental effects. Environmental factors such as disease, post-harvest handling and weather condition are generally can affect the kernel strength and lead to high broken rice. According to Phetmanyseng et al. (2019), the optimum time for harvesting was about 25 days after 75% flowering would increase the head rice recovery. In general, rice grain is harvested when 80 - 85% of paddy grains turn to yellow-straw colour where the moisture content at this stage at 20 - 22% at upon harvested and during drying the paddy grains the moisture content have to maintain at 13-14% prior the milling process. Delaying the harvesting time is caused to a high possibility of reducing the grain density and hardness that lead to high broken rice and insufficient head rice recovery (Anjana et al., 2019). Harvesting of immature paddy grains also can reduce the milling and head rice recovery due to grain being too slender and chalkiness (Parviz et al., 2014). High temperature is also a major defect in the grain filling efficacy and contributes to a high percentage of immature paddy grains and chalkiness (Buggenhout et al., 2014; Thompson and Mutters, 2006).

Amylose is one of the rice biochemical components affecting the cooking and eating quality of rice grains (Umar Farooq et al., 2019; Alex et al., 2017). It was observed that a low magnitude of GCV (below 10%) observed for AMY trait indicating a low degree of variability and limiting the scope for improvement through direct selection, thus phenotypic selection is might efficient which is indicated with moderate PCV value. This finding is in agreement with Mithilesh et al. (2017). The environmental factors had influences in AMY performances as indicated with the PCV value had double than the GCV. According to Misbah et al. (2018) and Li et al. (2018), the environmental factors had strong influences on amylose expression whereas, Ying et al. (2019) stated that amylose content is correlated with temperature factors. Although most Malaysians prefer rice grains with a medium amylose content (20-24%), some customers, particularly Chinese and those from Eastern Malaysia, prefer rice grains with low amylose content.

The rice breeder is always considered regards the genotype stability over environments are economically important. The desirable rice genotypes should have low G × E interactions in traits to get the desirable performance of cultivar over a wide range of environmental conditions. The univariate methods that were applied in this were able to identify the hybrid's stability over the environment which were ranked according to their smaller stability values. Although several issues which regard to AMMI and GGE models in analysing the G × E effect (Gauch, 2006; Yan et al.,2007), in favour of that both models have similarity in a combined analysis of variance (ANOVA) for additive parameters and singular value decomposition (SVD) for multiplicative parameters and the principal components (Gauch et al. (2008).

Materials and methods

Experimental design, locations and planting materials

In the study, 20 rice hybrids and two check inbred varieties, MR 269 and MR 263, were evaluated in eight environments for genotype vs environment stability and interaction (Table 1). The field trials carried out in four different locations: Bukit Merah Penang, Teluk Chengai Kedah, Bertam Penang, and Arau Perlis (Table 2). The first trial conducted during the main season 2016/2017 (November 2016 – Mac 2017), and the second trial occurred during the off-season 2017 (April – September 2017). The environments (the combination of season and location) covered agroclimatic differ in climates, soil profiles, and rainfall patterns. The experiment in each environment was designed using a Randomized Completely Block Design, with sub plotting sizes of 2.5 m 2.5 m for each genotype. When the crops were in the vegetative, reproductive, and heading stages, the fertiliser N, P2O5, and K2O rates were 120: 70: 80 kg/ha, applied in three splitting applications (15 - 20, 35 - 40 and 55 - 60 days after transplant, respectively). Post-emergence herbicide was used to control weeds, primarily narrow leaf and broadleaf. Insecticide chemicals were used to prevent pest attacks, primarily on rice thrips, stem borer, armyworm, leaf folder, leafcutter, brown planthopper, and rice bug. Meanwhile, the fungicide chemicals were used for disease management against foliar blast, panicle blast, and sheath blight.

Data collection and statistical analyses

ANOVA was performed in combined environments using the SAS programme version 9.4 and a random model. If there was a significant interaction between the genotype, location, and season, whereas genotype stability analysis was performed to identify stable genotype stability across environments. The data were measured in accordance with the IRRI's standard evaluation system (1996). Grain length, grain width, milled grain length, milled grain width, length to width ratio, milling recovery, head rice recovery, and amylose content were all evaluated quantitatively. The calculation for phenotypic and genotypic coefficients of variation with accordance to Singh and Chaudhary (1985) is as follows; PCV = $(\sigma^2 p / \overline{X}) \times 100\%$, GCV = $(\sigma^2 g / \overline{X}) \times 100\%$, where $\sigma^2 p$ is the phenotypic variance, $\sigma^2 g$ is the genotypic variance and $\overline{X}$ is the mean of the trait. PCV and GCV are categorised as low when the value is less than 10, moderate when less than 20, and high when the value is greater than 20 (Burton, 1952). _Broad sense heritability estimation according to the following equations: $\sigma^2_{ph} = \sigma^2_{g} + \sigma^2_{gl} + \sigma^2_{gs} + \sigma^2_{gls} + \sigma^2_{e}$, $\sigma^2_{g} = [(MS1 + MS4) - (MS2 + MS3)]/rls$ and broad-sense heritability $(h^2_B) = (\sigma^2_g / \sigma^2_{ph})/100$ where σ^2_g and σ^2_p are the genotypic and phenotypic standard deviation, respectively. The heritability classifies as low when the value is less than 30%, moderate (30 – 60%), and high when the value is greater than 60% (Johnson et al. (1955). All characters that showed significance GEI were subjected to stability analysis using univariate and multivariate methods. The univariate methods were genotypes superiority (Linn and Bin, 1988), static stability (Becker and Leon, 1988), Wrickie ecovelance (Wrickie, 1962), mean absolute rank (Nassar and Huehn, 1987) and coefficient of variation (Francis and Kannenberg, 1978). Multivariate stability analysis was performed using AMMI (Additive main effect and multiplicative interaction) (Gauch, 2006) and GGE biplot (Yan et al., 2000).

Conclusion

The quantitative parameters length to width ratio, head rice recovery, and amylose content were influenced by GE interaction, however, grain length, grain width, milled grain length, milled grain width, and milling recovery were not. All of the hybrids tested had a long, slender grain shape, which is preferred in the local market. The head rice recovery was determined to be satisfactory, with a recovery rate of more than 83.40% and the amylose content ranging from low to intermediate. The use of a combination of univariate and multivariate (AMMI and GGE biplot models) analysis methodologies allowed for the examination and selection of possible hybrids for physicochemical properties and their reaction to the environment. The univariate stability study revealed that the hybrids with the lowest G×E interaction and the most stable performance in head rice production were G2, G13, G8, G16, G7, G9, G6, G17, and G18. The univariate stability analysis revealed that hybrids with stable amylose performance were G7, G4, G19, G10, G5, G17, G3, G12, and G11. Meanwhile, AMMI and GGE biplot models revealed that hybrids with the lowest GE interaction for amylose character were found in G3, G4, G5, and G7, whereas all hybrids (except G5) performed consistently in head rice production in investigated environments.

Acknowledgements

This work supported by Development Project, Malaysian Plan 11th (Code P**21003004010001)**

References

Alex T, Maxwell DA, Richard A, Ibrahim S (2017) Evaluation of physicochemical characteristics of rice (*Oryza sativa* L.) varieties in Ghana. Int J Agric Sci. 7(8): 1342 - 1349.

Anjana JA, Rohitha Prasantha BD, Amaratunga KSP, Buddhi M (2019) Increased rate of potassium fertilizer at the time of heading enhances the quality of direct-seeded rice. Chem Biol Technol Agric. 5(22): 1 – 9.

Balakrishnan D, Subrahmanyam D, Badri J, Raju AK, Rao YV, Beerelli K, Mesapogu S, Surapaneni M, Ponnuswamy R, Padmavathi G, Babu VR, Neelamraju S (2016) Genotype × environment interactions of yield traits in backcross introgression lines derived from *Oryza sativa* cv. Swarna/*Oryza nivara*. Front Plant Sci. 7:1530. https://doi.org/10.3389/fpls.2016.01530

Bao JS (2012) Toward understanding the genetic and molecular bases of the eating and cooking qualities of rice. Cereal Foods World. 57(4): 148 - 156

Becker HC, Leon J (1988) Stability analysis in plant breeding. Plant Breeding. 10(1): 1 - 23.

Bharath MS, Madhan Mohan M, Vanniarajan C, Veranan AGV, Senthi N (2018) Genetic variability studies in ADT 43/Seeraga samba cross derivatives of rice (*Oryza sativa* L.). Electronic Journal of Plant Breeding. 9(4): 1450 - 1460.

Buggenhout J, Brijs K, Celus I, Delcour JA (2013) The breakage susceptibility of raw and parboiled rice: A review. Journal of Food Engineering. 117: 304 – 315.

Burton GW (1952) Quantitative inheritance in pearl millet (*Ptyphoides* L.). Agronomy Journal. 50: 503.

Caffagni A, Albertazzi G, Gavina G, Ravaglia S, Gianinetti A, Pecchioni N, Milc J (2013) Characterization of an Italian rice germplasm collection with genetic markers useful for breeding to improve eating and cooking quality. Euphytica. 194(3): 383 - 399.

Demelash B, Fekadu G, Hussein M (2019) Comparison of univariate and multivariate models to analyze stability of common bean (*Phaseolus vulgaris* L.) genotypes in Ethiopia. Agrotechnology. 8(1): 1 – 6.

Eder JO, Juan PXF, Onildo NJ (2014 AMMI analysis of the adaptability and yield stability of yellow passion fruit varieties. Sci Agric. 71(2): 139 – 145.

Finlay KW, Wilkinson GN (1963) Adaptation in a plant breeding programme. Aust. J. Agric. Res. 14: 742 - 754.

Fitzgerald MA, McCouch SR, Hall RD (2009) Not just a grain of rice: the quest for quality. Trends Plant Sci. 14(3):133–139.

Fox PN, Skovmand B, Thompson BK, Braun HJ, Cormier R (1990) Yield and adaptation of hexaploid spring *triticale*. Euphytica. 47: 57 – 64.

Francis TR, Kannenberg LW (1978) Yield stability studies in short season maize. I. A descriptive method for grouping genotypes. Can J Plant Sci. 5 (4): 1029 - 1034.

Gauch HG (2006) Statistical analysis of yield trials by AMMI and GGE. Crop Sci. 46(4): 1488 - 1500.

Gauch H, Hans-Peter P, Paolo A (2008) Statistical analysis of yield trials by AMMI and GGE: Further considerations. Crop Sci. 48:866 – 889.

IRRI (International Rice Research Institute) (2020). Retrieved on 17th Feb 2020 10:48am from http://www.knowledgebank.irri.org/step-by-step-production/postharvest/milling/producing-good-quality-milled-rice/milling-yields.

IRRI. Standard Evaluation System. INGER Genetic Resources. International Rice Research Institut, Los Banos Philippines. 1996.

Jiban S, Ujjawal KSK, Bidhya M, Sushil RS, Manoj K, Amrit PP, Rajendra PY (2020) Genotype × environment interaction and grain yield stability in Chinese hybrid rice. Ruhuna Journal of Science. 11(1): 47 - 58.

Johnson HW, Robinson HF, Comstock RE (1955) Estimates of genetic and environmental variances in soybean. Agronomy Journal. 47: 314 - 318.

Kang MS (1988) A rank-sum method for selecting high yielding, stable corn genotypes. Cereal Research Communications. 16: 113-115.

Kitara IO, Lamo J, Gibson P, Rubaihayo P (2019) Amylose content and grain appearance traits in rice genotypes. African Crop Science Journal. 27(3): 501 - 513

Li X, Lian W, Xin G, Xiuhong X, Xuhong W, Zhengjin X, Quan X (2018) Deciphering the environmental impacts on rice quality for different rice cultivated areas. Rice. 11(7): 2 - 10.

Lin CS, Binns MR (1988). A method of analyzing cultivar × location × year experiments: A new stability parameter. Theor Appl Genet. 76: 425 - 430.

Liu X, Guo T, Wan X, Wang H, Zhu M, Li A, Su N, Shen Y, Mao, Zhai H, Mao L, Wan J (2010) Transcriptome analysis of grain-filling caryopses reveals involvement of multiple regulatory pathways in chalky grain formation in rice. BMC Genomics. 11:730. https://doi.org/10.1186/1471-2164-11-730

Marie CC, Rosa PC, Jhoanne Y, Alice GL, Maria LV, Matty D (2019) Rice quality: How is it defined by consumers, industry, food scientists, and geneticists? Trends in Food Science and Technology. 92: 122 - 137.

Misbah R, Muhammad A, Muhammad I, Sultan A, Rana Ahsan RK, Mohsin R, Farrah S, Neelum S (2018) Estimation of amylose, protein and moisture content stability of rice in multi-locations. African Journal of Agricultural Research. 13(23): 1213 - 1219.

Mithilesh KS, Surendra S, Nautiyal MK, Pandey ID, Gaur AK (2017) Variability, heritability and correlation among grain quality traits in basmati rice (*Oryza sativa* L.). International Journal of Chemical Studies. 5(5): 309 - 312.

Nassar R, Huehn M (1987) Studies on estimation of phenotypic stability: tests of significance for nonparametric measures of phenotypic stability. Biometrics. 43:45 - 53.

Parviz F, Kharidah M, Aminah A, Md Atiqur RB, Mee, SN, Gauch Jr HG, Wickneswari R (2014) Genotype × environment assessment for grain quality traits in rice. Communication in Biometry and Crop Science. 9(2): 71 - 82.

Phetmanyseng X, Khamtai V, Senthong P, Jaquie M, Shu F (2018) Rice milling quality as affected by drying method and harvesting time during ripening in wet and dry seasons. Plant Production Science. 22(1): 98 - 106.

Richa S, Ritu RS, Namita S, Parmeshwar KS (2018) Genetic variation for morphological, grain yield and grain quality traits in rice landraces of Chhattisgarh. Advances in Bioresearch. 10(1): 128 - 132.

Rosniyana A, Hashifah MA, Shariffah Norin SA (2006) Quality evaluation of retailed packed Malaysian milled rice sold in the market. J Trop Agric Food Sci. 34(1): 45 - 55.

Shi W, Yin X, Struik, PC, Xie F, Schmidt RC, Jagadish KSV (2016) Grain yield and quality responses of tropical hybrid rice to high night-time temperature. Field Crop Research. 190:18 -25.

Siebenmorgen TJ, Grigg BC, Lanning SB (2013) Impacts of preharvest factors during kernel development on rice quality and functionality. Annu. Rev. Food. Sci. Technol. 4:101–115. https://doi.org/10.1146/annurev-food-030212-182644

Singh RK, Chaudhary BD (1985) Biometrical Methods in Quantitative Genetic Analysis. Kalyani Publishers, Ludhiana, India.

Thompson JF, Mutters RG (2006) Effect of weather and rice moisture at harvest on milling quality of California medium-grain rice. Transactions of the ASABE. 49: 435 - 440.

Umar Farooq M, Diwan JR, Mahantashivayogayya K, Vikas VK, Shakuntala NM (2019) Genetic evaluation of rice (*Oryza sativa*. L) genotypes for yield and nutritional quality traits. Journal of Experimental Biology and Agricultural Sciences. 7(2): 117 - 127.

Wricke G (1962) Uber eine Methode zur Erfassung der okologischen Streubreite in Feldversuchen. Z. Pfianzenzuchtg. 47: 92-96.

Yan W, Hunt LA, Sheng Q, Szlavnics Z (2000) Cultivar evaluation and mega-environment investigation based on GGE biplot. Crop Sci. 40: 597 - 60.

Yan W, Manjit SK, Baoluo M, Sheila W, Paul LC (2007) GGE Biplot *vs* AMMI Analysis of Genotype-by-Environment Data. Crop Sci. 47:641–653

Ying X, Yang Y, Liang H, Shanqing W, Ligeng J, Izhar A, Saif U, Quan Z (2019) Effects of meteorological factors on the yield and quality of special rice in different periods after anthesis. Agricultural Sciences. 10: 451 - 475.