Stability Analysis of Two-line Rice Hybrids (*Oryza sativa*) in Diverse Environments Utilizing AMMI Model

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**A B S T R A C T**

Genotype-environment interaction and stability analysis has been important for plant breeders and plays a vital role in identifying genotypes that are stable or unstable in each environment. Varieties that show low G x E interaction and high yield are desirable for crop breeders. The study was conducted in 2018 at six locations in India to (i) determine the presence of G x E of 171 single cross maize genotypes and (ii) To use the GGE biplot methodology to determine grain yield performance and stability of the genotypes evaluated across six environments. The effects of genotype and environment were significant (P < 0.01) for grain yield. Pooled ANOVA analysis of 171 genotypes in six environments (E1-E6) showed highly significant differences for environments, significance of variance due to G x E in pooled analysis also indicated the presence of significant genotype x environment interaction. Genotypes G4, G74, G72, G6, G5 and G107 were high yielders with high interaction with environment. Genotypes G73, G159, G97 have highest positive IPCV values and G91, G32, G75 and G132 have highest negative IPCV values indicating that these are highly unstable genotypes. The two-line system has been widely applied for rice breeding since it has many advantages such as, two-line system has more extensive germplasm resources that is beneficial to the development of heterosis, better hybrid seed production yields, absence of negative effects associated with sterility-inducing cytoplasm especially on grain quality.

**Introduction**

Rice (*Oryza sativa* L.) is one of the most important staple foods worldwide, providing almost one-quarter of the global dietary energy supply for humans. The demand for food continues to rise as the population rapidly grows; necessitating the significant increase in production rice and arable land is limited together with environmental degradation. Rice is one of the most important food crops for half of the world’s population. Worldwide, around 3.5 billion people depend upon rice for more than 20% of their calories requirement (Khush, 2013). India stands first in rice area with 44 million hectares and
second in production with 105 million tonnes after China (IRRI, 2016). Rice production has increased tremendously from 34.5 million tonnes in 1960–61 to 112.91 million tonnes 2017–18 by developing high yielding semi-dwarf varieties, through crop management, adoption of hybrid varieties and plant protection practices.

The concept of two-line breeding emerged as an alternative to the three-line approach in China (Yuan, 1997). The main advantages of two-line heterosis breeding include the ability to use a wide range of genotypes as male parents, absence of negative effects associated with sterility-inducing cytoplasm and no need for maintainer lines. Male sterility in temperature sensitive genic male sterile (TGMS) lines is heritable. International Rice Research Institute has shown that two-line hybrids derived from TGMS lines had higher frequency of heterotic combinations than three-line hybrids derived from CMS lines (Lopez and Virmani, 2000).

Genotype-environment interaction and stability analysis has been important for plant breeders and plays a vital role in identifying genotypes that are stable or unstable in each environment. Varieties that show low G x E interaction and high yield are desirable for crop breeders and farmers, because it indicates that the environments have less effect on the performance of genotypes and their yield is largely due to the genetic composition (Linnemann 1995).

Among multivariate methods, the additive main effect and multiplicative interaction analysis (AMMI) has been extensively applied in the statistical analysis of multi-environment cultivar trials. A strong GxE interaction slows down selection and identification of genotypes and makes recommendations difficult. To analyze GxE interaction and phenotypic stability, several methods have been proposed, specifically univariate and multivariate stability statistics methods. A combined analysis of variance can quantify the interactions and describe the main effects (Genotype and Environment) reported by (Lin et al., 1986). The effectiveness of AMMI procedure has been clearly demonstrated by various authors and more specifically by Zobel et al. (1988) in soybean, Crossa et al. (1990) in maize and Mahalingam et al. (2018) in greengram using multilocation trial data. Ponnuswamy et al., 2017 reported in a study that AMMI and GGE biplots analyses were successful in assessing genotype by environment interaction in hybrid rice trials and aided in the identification of stable and adaptable rice hybrids with higher mean and stable yields. Jain et al., (2018) reported that estimates of genotype x environment interaction and additive main effect were significant for all the traits viz., grain yield, tiller/plant, plant height and panicle weight. Shams Shaila Islam et al., 2020 reported that highly significant differences were shown from the combined analysis for environments with grain yields, revealing that environments were different and indicated change ability between the genotypes and their interactions.

Materials and Methods

161 rice hybrids developed using 161 varieties crossed with one a TGMS line, PLIR75589TGMS at Hyderabad during November 2017 to May, 2018 seed production season. 161 hybrids along with 8 hybrid checks Viz., 25P35, 27P22, 27P31, 28P67, 27P37, PHB71, Arize 6444 Gold, US312 and 2 varietal checks Viz., MTU1010 and NDR-359 were evaluated at six locations viz., Patna (E1), Purnea (E2) in Bihar, Lucknow(E3), Gosaiganj (E4), Barabanki (E5) and Prayagraj (E6) in Uttar Pradesh during 2018 rainy season of 2018 from, June to October period. The evaluation sites are in
the north central part of India (Figure 1). A standard hybrid rice cultivation of practice as recommended by IIRR was adopted at each site during crop growth period. Evaluations were done under irrigated conditions. The genotypes were planted in a randomized complete block design with two replications. Each plot consisted 2-rows of 3.5-meter-long with 0.5 meter allay, with 20 cm space between rows and 15 cm between plants, accommodating 40 plants per entry per replication. Seedlings were raised in 5 meter by 1 meter raised nursery beds and transplanted into main field after puddling with 21-25 days old seedlings. Yield was calculated as kg/ha after extrapolating yield per 40 plants to 330000 plants/ha (15 x 20cm spacing) at standard 14 % moisture for standardisation across entries as follows

\[
\text{Yield (T/ha)} = \frac{(\text{Yield/40 plants}*330000*(100-\text{Moisture})/86)}{1000000}
\]

Analysis of variance was computed for the individual environment as well as for across environments. The significance of all effects was tested against the mean square of error.

The AMMI method was applied with additive effects to 171 genotypes in six environments, and multiplicative was used for GxE interaction. According to Sabaghnia et al. (2008), the AMMI method at first adjusts additive effects for host genotypes and environments through the normal additive analysis of variance (ANOVA) technique and fits multiplicative effects for GxE by PCA. It affords a symbolic view of the transformed GxE interaction for any interpretation (Kempton, 1984). The statistical analysis computed using R programme.

**Results and Discussion**

Understanding of GxE interaction in plant species is of importance because it has implications for economic yield. In view of influence of environmental factors on crop growth, it is necessary to explore variation among genotypes (Anandan, 2011). From Table 1, The ANOVA showed that mean squares due to genotypes were highly significant for grain yield in all (E1 to E6) environments, indicating differential performances of genotypes across environments, whereas ANOVA for replications showed no significant differences indicating the within non-significant location variation. Combined ANOVA analysis (Table 2) of 171 genotypes in six environments (Patna, Purnia, Lucknow, Gosaiganj, Barabanki, Prayagraj) showed highly significant differences for environments, significance of variance due to G x E, indicated the presence of significant genotype x environment interaction. The significance of genotypes mean squares indicated that genotypes differed among themselves and there existed a considerable variability irrespective of the effect of environments on the characters under study. The mean squares due to G x E interaction when tested against pooled error were significant for grain yield, hence the data was subjected to AMMI analysis.

In this study, the analysis of variance showed significance for PCA1 PCA2, PCA3,PCA4 and PCA5 (Table 3). Among these, PCA 1, PCA2 and PCA3 together recorded 70.9 percent of total sum of squares. Hence, IPCA1, IPCA2, IPCA3 may be used for explaining the G x E interaction within study.

Table 5 shows IPCA1 and IPCA2 scores that characterize the interaction of a genotype across environments as well as relationships between genotypes and environments. According to Yan and Hunt (2001) and Mohammadi et al. (2007), a genotype with a positive IPCA score in several environments must neutralize negative interactions in other
environments. Hence, these scores exhibit an unequal genotype reaction to the environment. Nevertheless, both positive and negative signs, as well as genotypes and environments using large IPCA scores, have strong large interactions and are stable. For grain yield the genotypes G72 (9.954 T/Ha), G74 (9.798 T/Ha), G58 (9.672 T/Ha), G107 (9.621 T/Ha), G4 (9.591 T/Ha), G6 (9.521 T/Ha), G5 (9.318 T/Ha), G83 (9.284 T/Ha), G16 (9.282 T/Ha) were the top mean yielders across the location (Table 4).

**BiPlot**

The AMMI biplot with the genotype and environment main effects for grain yield on the x-axis and the IPCA1 scores on the y-axis is presented in Fig. 2. There are two basic AMMI biplots, the AMMI1 biplot where the main effects (genotype mean and environment mean) and IPCA1 scores for both genotypes and environments are plotted against each other and the AMMI 2 biplot where scores for IPCA1 and IPCA2 are plotted.

Genotypes close to the horizontal line have small interactions and are more stable than those farther from it. The biplot (Figure: 2) revealed large variability among the six test environments and variability among the 171 genotypes tested. The genotypes which are on or close to the horizontal line indicate the IPCA scores for these genotypes are nearer to zero and therefore had small interaction with the environments. G16 was right on the horizontal line with high mean value indicating that G16 is consistent high yielder across the environments tested. G169, G82, G68, G122 & G151 were average to high yielders and were on the horizontal line indicating that they are average to high yielders with stability across environments. Genotypes G4, G74, G72, G6, G5 and G107 were high yielders with high interaction with environment. The genotypes G-99, G-85, G-60 and G-103 are poor yielders across environments and are not suitable across growing environments. Genotypes G73, G159, G97 have highest positive IPCV values and G91, G32, G75 and G132 have highest negative IPCV values indicating that these are highly unstable genotypes. Mary Ann et al., 2019 in their study on high zinc breeding material of IRRI indicated that the AMMI and GGE analyses showed significant genotype, environment, and G X E effects for Zn and YLD across seasons. Many earlier studies have also reported significant genotypic and G X E effects for yield, yield components, and grain micronutrients in rice (Chandel et al. 2010; Rerkasem et al. 2015; Nasrullah 2011; Ajmera et al. 2017).

In AMMI 2 biplot (Figure: 3) the environmental scores are joined to the origin by side lines. Environments with short vectors do not exert strong interactive forces. Those with longer vectors exerts strong interaction. In this study Barabanki (E5) had shorter vector and do not exert strong interactions with genotypes whereas environment Prayagraj (E6) has the longest vector indicating strong GxE interaction at this location. Environments like, Patna (E1), Purnia (E2), Lucknow(E3) and Gosaiganj (E4) had longer vectors and had good interaction with genotypes. The genotypes occurring close together on the plot will tend to have similar yields in all environments, while genotypes far apart may either differ in mean yield or show a different pattern of response over the environments. Hence, the genotypes near the origin are not sensitive to environmental interaction and those distant from the origins are sensitive and have large interaction.

The quadrants proposed by Olivoto, Lúcio, Da silva, Marchioro, et al. (2019) in the following biplot (Figure 3.) represent four classifications regarding the joint
interpretation of mean performance and stability. The genotypes or environments included in quadrant I can be considered unstable genotypes or environments with high discrimination ability, and with productivity below the grand mean. Genotypes like G138, G97, G48, G84, G94, G86, G43, G31 and checks like G9 (MTU-1010) are unstable genotypes. Environments like Purnia (E2) and Prayagraj (E6) have high discrimination ability. In quadrant II are included unstable genotypes, although with yield higher than the grand mean. The environments included in this quadrant deserve special attention since, in addition to providing high magnitudes of the response variable, they present a good discrimination ability. Environments like Patna (E1), Lucknow (E3) and Barabanki (E5) represent such environments in the study. Genotypes like G72, G107, G46, G157, G58, G46, G57 and check hybrid like Arize6444 Gold registered high yield above mean but unstable. Gosiaganj location was right on the vertical line and can be effectively used to select genotypes which represent the overall trend across six locations. Genotypes within quadrant III have low productivity but can be considered stable due to the lower values of WAASB. The lower this value, the more stable the genotype can be considered. The environments included in this quadrant can be considered as poorly productive and with low discrimination ability. Genotypes like, G81, G100, G19, G125, G106, G14, G121, G108, G14, G64, G67 etc are considered stable genotypes with average to poor yields.

**Table 1** Mean squares of analysis of variance (ANOVA) for grain yield across 6 locations

| Source of Variation | DF | Mean Sum of squares for grain Yield |
|---------------------|----|-----------------------------------|
|                     |    | E1 | E2 | E3 | E4 | E5 | E6 |
| Genotype           | 170| 3.752*** | 4.455*** | 2.824*** | 2.3133*** | 3.225*** | 3.519*** |
| Rep                | 1  | 0  | 0.001 | 0.0057 | 0.0014 | 0.007 | 0.001 |
| Error              | 170| 0.012 | 0.013 | 0.0133 | 0.0125 | 0.013 | 0.014 |

**Table 2** Mean squares of analysis of variance (ANOVA) for grain yield across 6 locations

| Source of Variation | DF | Mean squares for Grain Yield |
|---------------------|----|-----------------------------|
| Hybrid              | 170| 16.74***                    |
| Rep                 | 1  | 0.01                        |
| Location            | 5  | 97.3***                     |
| GE*Location         | 850| 0.67***                     |
| Residuals           | 1025| 0.01                       |
Table 3 AMMI analysis for grain yield (T/Ha) of rice Hybrids across 6 locations

| Source of Variation | Df | SS     | Explained TSS (%) | MS   | F     | p -value | Explained (%) |
|---------------------|----|--------|-------------------|------|-------|----------|---------------|
| Environment (E)     | 5  | 486.52 | 10.85             | 97.305 | 34884.5 | 2.6712E-13*** |               |
| Replicate/Environment | 6  | 0.02   | 0.00              | 0.003 | 0.21  | 0.9726   |               |
| Genotype (G)        | 170 | 2845.4 | 63.45             | 16.737 | 1281.0 | <0.001*** |               |
| Interaction (GE)    | 850 | 569.6  | 12.70             | 0.670 | 51.29 | <0.001*** |               |
| IPCA1               | 174 | 157.9  | 3.52              | 0.908 | 69.48 | <0.0001*** | 27.7          |
| IPCA2               | 172 | 133.5  | 2.98              | 0.777 | 59.41 | <0.0001*** | 23.4          |
| IPCA3               | 170 | 112.8  | 2.51              | 0.663 | 50.77 | <0.0001*** | 19.8          |
| IPCA4               | 168 | 91.3   | 2.04              | 0.544 | 41.59 | <0.0001*** | 16            |
| IPCA5               | 166 | 74.09  | 1.65              | 0.447 | 34.16 | <0.0001*** | 13            |
| Residual            | 1020 | 13.33 | 0.30              | 0.0131 | NA    | NA       |               |
| Total               | 2901 | 4484.4 | 100.00            | 1.546 | NA    | NA       | <NA>          |

Table 4 High Yielding rice hybrids and their IPCA score for grain yield (T/Ha)

| Genotype Code | Genotype                | Grain Yield (T/ha) | IPCA1  | IPCA2  | IPCA3  | IPCA4  | IPCA5  |
|---------------|-------------------------|--------------------|--------|--------|--------|--------|--------|
| G4            | 27P37                   | 9.591              | 0.09102 | -0.258 | -0.074 | 0.2643 | -0.3369|
| G5            | 28P67                   | 9.318              | -0.0640 | 0.178  | -0.050 | 0.2936 | 0.1082 |
| G6            | BSBArize6444 Gold       | 9.521              | 0.1994 | 0.311  | -0.390 | 0.0268 | 0.4713 |
| G16           | PLIR75589TGMS/IR07A250  | 9.282              | 0.00790 | 0.206  | 0.4502 | -0.146 | 0.1168 |
| G58           | PLIR75589TGMS/PL1823315 | 9.672              | -0.1355 | -0.304 | -0.128 | 0.2659 | 0.2398 |
| G72           | PLIR75589TGMS/PLADT44   | 9.954              | 0.4226 | 0.228  | 0.0804 | -0.1724 | -0.5531|
| G74           | PLIR75589TGMS/PLASD20   | 9.798              | 0.2819 | 0.1112 | 0.1104 | -0.2761 | 0.01249|
| G83           | PLIR75589TGMS/PLChampa  | 9.284              | -0.0651 | 0.1951 | 0.1835 | -0.2428 | -0.1721|
| G107          | PLIR75589TGMS/PLIR547452231983 | 9.621 | 0.2017 | 0.5319 | 0.2832 | 0.1302 | 0.1709 |
Table 5 Performance of genotypes and their IPCA1 score for yield (mt/ha)

| Code | Hybrid   | Yield (T/ha) | IPCA1 | Code  | Hybrid | Yield (T/ha) | IPCA1 |
|------|----------|--------------|-------|-------|--------|--------------|-------|
| G1   | 25P35    | 7.29         | -0.216| G47   | Hyb-73 | 9.08         | 0.246 |
| G2   | 27P22    | 8.72         | 0.309 | G48   | Hyb-75 | 7.46         | -0.160|
| G3   | 27P31    | 8.88         | 0.305 | G49   | Hyb-77 | 8.07         | -0.249|
| G4   | 27P37    | 9.59         | 0.091 | G50   | Hyb-79 | 7.89         | -0.107|
| G5   | 28P67    | 9.32         | -0.064| G51   | Hyb-81 | 7.77         | 0.275 |
| G6   | Arize6444 | 9.52         | 0.199 | G52   | Hyb-83 | 6.10         | -0.313|
|      | Gold     |              |       |       |        |              |       |
| G7   | PHB71    | 8.30         | -0.100| G53   | Hyb-86 | 8.15         | -0.035|
| G8   | US312    | 7.88         | 0.233 | G54   | Hyb-87 | 7.87         | 0.187 |
| G9   | MTU1010  | 4.96         | -0.361| G55   | Hyb-89 | 7.21         | -0.108|
| G10  | NDR359   | 6.42         | -0.187| G56   | Hyb-91 | 7.36         | 0.286 |
| G11  | Hyb-02   | 7.64         | 0.234 | G57   | Hyb-93 | 8.07         | 0.075 |
| G12  | Hyb-04   | 7.54         | 0.316 | G58   | Hyb-95 | 9.67         | -0.136|
| G13  | Hyb-06   | 8.44         | -0.078| G59   | Hyb-97 | 7.70         | 0.113 |
| G14  | Hyb-08   | 7.30         | -0.161| G60   | Hyb-99 | 3.82         | 0.120 |
| G15  | Hyb-10   | 8.19         | 0.106 | G61   | Hyb-10 | 7.28         | -0.010|
| G16  | Hyb-12   | 9.28         | 0.008 | G62   | Hyb-10 | 7.11         | -0.037|
| G17  | Hyb-14   | 7.53         | -0.099| G63   | Hyb-10 | 8.89         | 0.092 |
| G18  | Hyb-16   | 8.26         | 0.024 | G64   | Hyb-10 | 7.42         | 0.049 |
| G19  | Hyb-18   | 7.14         | -0.034| G65   | Hyb-10 | 8.15         | 0.072 |
| G20  | Hyb-20   | 8.77         | -0.198| G66   | Hyb-11 | 7.81         | 0.126 |
| G21  | Hyb-22   | 8.97         | -0.258| G67   | Hyb-11 | 7.35         | 0.005 |
| G22  | Hyb-24   | 7.24         | 0.076 | G68   | Hyb-11 | 8.40         | 0.006 |
| G23  | Hyb-26   | 8.59         | 0.195 | G69   | Hyb-11 | 7.85         | 0.367 |
| G24  | Hyb-28   | 7.28         | -0.069| G70   | Hyb-12 | 7.77         | -0.045|
| G25  | Hyb-30   | 7.77         | -0.311| G71   | Hyb-12 | 7.84         | -0.007|
| G26  | Hyb-32   | 5.66         | -0.495| G72   | Hyb-12 | 9.95         | 0.423 |
| G27  | Hyb-34   | 8.12         | 0.242 | G73   | Hyb-12 | 8.44         | 0.189 |
| G28  | Hyb-36   | 7.96         | 0.281 | G74   | Hyb-12 | 9.80         | 0.282 |
| G29  | Hyb-38   | 7.63         | 0.264 | G75   | Hyb-12 | 6.38         | -0.579|
| G30  | Hyb-40   | 7.63         | 0.146 | G76   | Hyb-13 | 6.61         | 0.043 |
| G31  | Hyb-42   | 6.12         | -0.538| G77   | Hyb-13 | 6.70         | -0.013|
| G32  | Hyb-44   | 9.19         | -0.367| G78   | Hyb-13 | 7.86         | 0.054 |
| G33  | Hyb-46   | 7.05         | -0.175| G79   | Hyb-13 | 7.73         | -0.101|
| G34  | Hyb-48   | 8.79         | 0.428 | G80   | Hyb-13 | 6.96         | -0.030|
| G35  | Hyb-50   | 7.66         | 0.036 | G81   | Hyb-14 | 7.54         | -0.130|
| G36  | Hyb-52   | 7.87         | 0.296 | G82   | Hyb-14 | 8.56         | 0.005 |
| G37  | Hyb-54   | 7.86         | -0.059| G83   | Hyb-14 | 9.28         | -0.065|
| G38  | Hyb-55   | 7.83         | 0.015 | G84   | Hyb-14 | 6.93         | -0.291|
| Code | Hybrid  | Yield (T/ha) | IPCA1 | Code | Hybrid  | Yield (T/ha) | IPCA1 |
|------|---------|--------------|-------|------|---------|--------------|-------|
| G39  | Hyb-58  | 7.96         | 0.086 | G85  | Hyb-149 | 4.48         | 0.186 |
| G40  | Hyb-60  | 5.48         | -0.346| G86  | Hyb-151 | 5.08         | -0.475|
| G41  | Hyb-62  | 6.53         | -0.049| G87  | Hyb-153 | 7.50         | -0.084|
| G42  | Hyb-63  | 7.04         | 0.133 | G88  | Hyb-155 | 7.26         | 0.215 |
| G43  | Hyb-65  | 7.53         | 0.277 | G89  | Hyb-157 | 6.94         | 0.031 |
| G44  | Hyb-67  | 9.26         | -0.100| G90  | Hyb-159 | 7.52         | -0.055|
| G45  | Hyb-69  | 8.18         | 0.208 | G91  | Hyb-161 | 5.81         | -0.673|
| G46  | Hyb-71  | 9.15         | 0.258 | G92  | Hyb-163 | 8.27         | -0.134|
| G93  | Hyb-165 | 7.42         | -0.046| G137 | Hyb-253 | 7.83         | 0.134 |
| G94  | Hyb-167 | 6.24         | -0.376| G138 | Hyb-255 | 5.49         | -0.623|
| G95  | Hyb-169 | 5.84         | 0.028 | G139 | Hyb-257 | 5.46         | -0.285|
| G96  | Hyb-171 | 7.61         | 0.040 | G140 | Hyb-259 | 8.52         | 0.199 |
| G97  | Hyb-173 | 6.56         | 0.644 | G141 | Hyb-261 | 8.15         | -0.027|
| G98  | Hyb-175 | 7.97         | 0.001 | G142 | Hyb-263 | 8.05         | 0.217 |
| G99  | Hyb-177 | 4.09         | 0.025 | G143 | Hyb-265 | 8.29         | 0.200 |
| G100 | Hyb-179 | 7.61         | 0.171 | G144 | Hyb-267 | 7.95         | 0.215 |
| G101 | Hyb-181 | 5.51         | 0.325 | G145 | Hyb-269 | 7.98         | 0.306 |
| G102 | Hyb-183 | 6.87         | -0.162| G146 | Hyb-271 | 7.07         | -0.331|
| G103 | Hyb-185 | 3.21         | -0.110| G147 | Hyb-273 | 5.28         | 0.412 |
| G104 | Hyb-187 | 7.58         | 0.127 | G148 | Hyb-275 | 7.93         | 0.124 |
| G105 | Hyb-189 | 6.41         | -0.367| G149 | Hyb-277 | 6.71         | -0.278|
| G106 | Hyb-191 | 7.24         | 0.019 | G150 | Hyb-279 | 8.16         | -0.184|
| G107 | Hyb-193 | 9.62         | 0.202 | G151 | Hyb-282 | 8.47         | -0.004|
| G108 | Hyb-195 | 7.28         | -0.088| G152 | Hyb-283 | 7.20         | 0.291 |
| G109 | Hyb-197 | 8.20         | 0.142 | G153 | Hyb-285 | 6.41         | 0.086 |
| G110 | Hyb-199 | 5.94         | -0.111| G154 | Hyb-287 | 8.23         | 0.116 |
| G111 | Hyb-201 | 8.48         | 0.229 | G155 | Hyb-289 | 7.70         | 0.168 |
| G112 | Hyb-203 | 7.78         | 0.199 | G156 | Hyb-292 | 6.71         | 0.363 |
| G113 | Hyb-205 | 7.80         | 0.329 | G157 | Hyb-293 | 9.27         | 0.137 |
| G114 | Hyb-207 | 7.89         | -0.087| G158 | Hyb-295 | 7.44         | 0.169 |
| G115 | Hyb-209 | 8.05         | -0.072| G159 | Hyb-297 | 8.32         | 0.138 |
| G116 | Hyb-211 | 6.73         | -0.069| G160 | Hyb-299 | 8.54         | 0.096 |
| G117 | Hyb-213 | 6.75         | -0.110| G161 | Hyb-301 | 8.00         | 0.304 |
| G118 | Hyb-215 | 6.79         | -0.320| G162 | Hyb-303 | 8.79         | 0.110 |
| G119 | Hyb-217 | 7.66         | -0.318| G163 | Hyb-306 | 6.97         | 0.094 |
| G120 | Hyb-219 | 8.84         | 0.186 | G164 | Hyb-307 | 8.79         | -0.150|
| G121 | Hyb-221 | 7.35         | -0.273| G165 | Hyb-309 | 6.98         | 0.285 |
| G122 | Hyb-223 | 8.02         | -0.023| G166 | Hyb-311 | 8.03         | 0.306 |
| G123 | Hyb-225 | 6.83         | 0.206 | G167 | Hyb-313 | 9.24         | 0.448 |
| G124 | Hyb-227 | 7.46         | 0.038 | G168 | Hyb-315 | 7.20         | 0.028 |
| G125 | Hyb-229 | 7.29         | -0.142| G169 | Hyb-317 | 8.39         | 0.042 |
| G126 | Hyb-231 | 6.04 | -0.055 | G170 | Hyb-319 | 3.81 | 0.361 |
|------|---------|------|--------|------|---------|------|-------|
| G127 | Hyb-233 | 7.90 | 0.325  | G171 | Hyb-321 | 6.40 | -0.142|
| G128 | Hyb-235 | 8.97 | 0.084  |      |         |      |       |
| G129 | Hyb-237 | 8.43 | 0.296  |      |         |      |       |
| G130 | Hyb-239 | 8.08 | -0.129 |      |         |      |       |
| G131 | Hyb-241 | 8.44 | -0.213 |      |         |      |       |
| G132 | Hyb-243 | 7.50 | 0.086  |      |         |      |       |
| G133 | Hyb-245 | 7.36 | -0.051 |      |         |      |       |
| G134 | Hyb-247 | 5.60 | -0.313 |      |         |      |       |
| G135 | Hyb-249 | 7.70 | -0.165 |      |         |      |       |
| G136 | Hyb-251 | 6.97 | 0.019  |      |         |      |       |

**Environments**

| Environment | Location | Latitude  | Longitude | State            |
|-------------|----------|-----------|-----------|------------------|
| E1          | Patna    | 25.71797  | 85.38025  | Bihar            |
| E2          | Purnia   | 25.84294  | 87.26771  | Bihar            |
| E3          | Lucknow  | 26.74992  | 80.78606  | Uttar Pradesh    |
| E4          | Gosaiganj| 26.6353   | 81.07975  | Uttar Pradesh    |
| E5          | Barabanki| 26.92813  | 81.10857  | Uttar Pradesh    |
| E6          | Allahabad| 25.56773  | 81.83063  | Uttar Pradesh    |

**Figure 1** Locations details where yield trials were planted

**Figure 2** AMMI BiPlot 1
Figure 3 AMMI BiPlot 2

Figure 4 Y x WAAS BiPlot
The genotypes within the quadrant IV are highly productive and broadly adapted due to the high magnitude of the response variable and high stability performance (lower values of WAASB). Genotypes like, G4, G74,G3, G83, G16, G7, G78, G44, G120 & G46 are high yielding and fairly stable hybrids across tested environments.

This study indicated the presence of large GXE interaction across the tested environments. The genotype G16 (PLIR75589TGMS/IR07A250) is a consistent high yielder across the environments tested and is recommended for cultivation in the sampled environments. G169, G82, G68 G122 & G151 are the second set of high yielding stable hybrids cross environments. Genotypes G4, G74, G72, G6, G5 and G107 were high yielders with high interaction with environment and therefore can be recommended to specific locations were they are performing well with lease environmental interaction.

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