Indian Journal of Agricultural Sciences **96** (4): 516–522, April 2026/Article
https://doi.org/10.56093/ijas.v96i4.164644

Identification of stable and high yielding early rice (*Oryza sativa*) lines across seasons using GGE Biplot analysis

SREEDHAR SIDDI[1]*, D ANIL [2] and R ABDUL FIYAZ[3]

Professor Jayashankar Telangana Agricultural University, Rajendranagar, Hyderabad, Telangana 500 030, India

Received: 10 February 2025; Accepted: 20 March 2026

ABSTRACT

The present study aimed to evaluate grain yield performance, stability, and adaptability of nine early-maturing rice (*Oryza sativa* L.) genotypes was conducted at Agricultural Research Station (Professor Jayashankar Telangana Agricultural University, Rajendranagar, Hyderabad) Kunaram, Peddapalli, Telangana during summer 2018–19, rainy (*kharif*) 2019, summer 2019–20, and rainy (*kharif*) 2020. The comprehensive analysis of variance unequivocally revealed statistically significant influences from lines, seasons, and their interaction, indicating a complex interplay that governs grain yield variability. The findings of GGE biplot methodology demonstrated that greatest variation of total variation was concentrated in environmental factors, subsequently in line impacts and their interactions influencing grain yield. More than 85% of the total variation was captured by the first two principal components, with PC1 and PC2 explaining 68.8% and 18.3% of the variation, respectively. In the GGE biplot genotype view, genotypes G_1 and G_5 were identified as high-yielding and stable, as indicated by their proximity to the biplot origin suggesting broad adaptability and minimal G×E interaction. The GGE biplot facilitated the identification of mega-environments through polygon, wherein the top-performing lines included G_3, G_5, and G_1 in Mega Environment 1, while G_7 stood out as the elite line in Mega Environment 2. G_3 was closely aligned with the ideal line followed by G_5 and G_1 in biplot's average-environment coordination (AEC) view, conclusively expressing remarkable yield and stability due to their extensive adaptability under the seasons tested suggests strong potential for inclusion in early rice varietal development and multi-environment breeding programmes.

Keywords: Grain yield, GGE Biplot, Polygon, Rice, Stability analysis

In Asia, rice cultivation serves as the cornerstone of agriculture, contributing to more than 90% of global rice production and consumption (Sackey *et al.* 2025). On the other hand, rice is farmed on approximately 50 mha in India, yielding around 145 mt (Department of Agricultural and Farmers Welfare 2026). Despite a consistent increase in production, the yield per hectare remains relatively low at 3.78 t/ha in India, particularly in contrast to other rice growing nations (Kesh *et al.* 2021). The future challenge lies in enhancing rice productivity, particularly in light of diminishing arable land, climate change, and the growing gap between production and consumption (Poli *et al.* 2018). In India, climatic variability contributed to an average annual decline of 3.93% in rice production between 1998 and 2019 (Gupta *et al.* 2025). Earliness is one of the most important agronomic traits of rice that determines the regional and seasonal adaptability and has a significant influence on the grain yield of rice varieties (Hori *et al.* 2016, Zhou *et al.* 2021, Liang *et al.* 2024), particularly in cropping systems with limited water supply as early maturity enables the timely completion of the crop prior to critical depletion of soil moisture (Bueno and Lafarge 2017) and reduces risk associated with pathogen proliferation or increased insect populations (Seck *et al.* 2023). Early maturing high yielding rice lines with fewer days to flower are valuable donor source in breeding programmes to develop superior early maturing varieties.

Investigating the interaction between lines, and seasons as well as locations is essential for understanding the adaptability and stability of lines suitable for cultivation in larger areas. Variations in yield among lines tested over different seasons can be significant, and driven by factors such as soil fertility, unforeseen rainfall, and different biotic and abiotic stresses (Kang 1993). Such variability in response to diverse environmental conditions is referred to as genotype by environment interaction (GEI). These insights are crucial for establishing improved selection strategies and figuring out the optimal environments for determining

---

[1]Agricultural Research Institute, Professor Jayashankar Telangana Agricultural University, Rajendranagar, Hyderabad, Telangana; [2]Agricultural College, Dichpally, Nizamabad District, Professor Jayashankar Telangana Agricultural University, Telangana; [3]ICAR-Indian Institute of Rice Research, Rajendranagar, Hyderabad, Telangana. *Corresponding author email: siddu.35@gmail.com

the lines that enhance grain yield (Gauch and Zobel 1996). Therefore, it is imperative to consider the GEI effects while assessing lines for the purpose of developing desired new varieties (Atlin *et al.* 2000).

The current investigation employs GGE biplot methodology to systematically rank genotypes, identify 'ideal' genotypes, and assess the stability and adaptability of nine early rice lines across diverse environments. Utilizing a polygon view to illustrate the 'which-won-where' pattern, this study also effectively delineates the winning lines within their corresponding mega-environments.

MATERIALS AND METHODS

The present experiment was conducted during summer 2018–19 (E_1); rainy (*kharif*) 2019 (E_2); summer 2019–20 (E_3), and rainy (*kharif*) season of 2020 (E_4) at Agricultural Research Station (Professor Jayashankar Telangana Agricultural University, Rajendranagar, Hyderabad) Kunaram (18.6°N and 79°E, with an elevation of 231 m amsl), Peddapalli, Telangana. The experiment was laid out in a randomized complete block design (RCBD) with three replications. The soil composition is silty loam, exhibiting a *p*H of 7.43 and an electrical conductivity of 0.26 dS/m. The experimental material consisted of eight early maturing lines from the International Rice Research Institute (IRRI), sourced through the International Genetic Evaluation of Rice Nurseries (INGER) *via* Indian Institute of Rice Research (IIRR), Hyderabad. In total, nine genotypes, including the eight lines and one check, were assessed across the four environments at the Agricultural Research Station, Kunaram aiming to adapt the lines for both growing seasons (Table 1). Twenty five-days old, seedlings were planted in a 20 cm × 15 cm spacing and plot size of 11.40 m^2, and standard agronomic practices along with effective control measures were implemented. The grain yield was assessed at the stage of physiological maturity, with measurements standardized to a 13% moisture content. The plot-level yields expressed in kg/plot were subsequently changed to kg/ha.

Statistical analysis: The use of multivariate models such as the additive main effects and multiplicative interaction (AMMI) model and the genotype main effects and genotype by environment interaction effects (GGE) model is on the rise for visual data analysis across multiple environments to elucidate interactions between genotypes and environments (Gouch 2006). The AMMI approach employs reciprocal investigation of variance (ANOVA) alongside principal component analysis (PCA) to derive additive main effects and interaction effects, correspondingly with the genotype-environment interaction (GEI) effects depicted in a biplot. In contrast, GGE biplots illustrate both genotype (G) and GEI (genotype by environment) variations (Kang 1993) through environment-centered PCA. While both models offer unique advantages, GGE outperforms AMMI in its capacity to reveal the "what-won-where" aspect, enabling the identification of GEI crossovers and mega-environments.

The present investigation involved conducting trials in each of the four seasons, treating each as a distinct environment for stability analysis. The statistics from each season was individually accustomed and analysed through an analysis of variance to examine variances. Subsequently, statistics from four seasons was combined for a pooled analysis of variance, evaluating nine lines across the seasons to determine the presence of significant variations. The analysis of variance revealed significant effects for genotypes, environments, and their interaction concerning grain yield, emphasizing the utility of GGE biplot analysis in finding stable lines. In rice, many rice researchers have previously employed the GGE biplot methodology for genotypic assessment, mega-environment evaluation, and recognizing stable lines (Kang 1993, Sharifi *et al.* 2017, Balakrishnan *et al.* 2020, Senguttuvel *et al.* 2021, Suman *et al.* 2021, Rahman *et al.* 2025). The performance of the nine lines tested over four seasons across two years was analysed using the GGE biplot stability model, employing R and PB Tools Software.

Table 1 Early rice lines and their designation for four environments

*Early rice line	Name of the line	Environment
G_1	IR 12N 198	Summer 2018–19 (E_1)
G_2	IRRI 123	*kharif* 2019 (E_2)
G_3	IR 12N 242	Summer 2019–20 (E_3)
G_4	IRRI 168	*Kharif* 2020 (E_4)
G_5	IRRI 186	
G_6	IR 14K 642	
G_7	IRRI 179	
G_8	IR 14K 107	
G_9	KNM 118	

*Early, 90–100 days (number of days required for 50% flowering under four seasons).

RESULTS AND DISCUSSION

Analysis of variance and mean performance: Analysis of variance (ANOVA) concerning grain yield among nine rice varieties assessed over four seasons using the GGE model (Table 2). The outcomes of the ANOVA indicated that the effects of genotypes (G), environments (E), and the interaction between genotypes and environments (GEI) were all significant, highlighting line's variable reactions to diverse seasons and their impact on grain yield. Similar results can be seen from the research findings of Bose *et al.* (2014), Huang *et al.* (2017), Ponnuswamy *et al.* (2018), Suman *et al.* (2021), Rahman *et al.* (2025) regarding grain yield. Sources of variation explained (%) demonstrated for overall variation of 26.67% attributed to varieties, 54.54% to the seasons, and 14.69% to the interaction, all of which influenced grain yield. These results indicated that season was the principal source of variation. Bueno and Lafarge (2017) noted that grain yield was significantly greater in the summer compared to the rainy season in irrigated rice

Table 2 Analysis of variance across four seasons for grain yield

Source of variation	DF	Grain yield (kg/ha)	
		MS	% SS explained
Genotypes	8	14858596.74*	26.67
Environments	3	81014851.70*	54.54
Varieties × Environments	24	2729029.75**	14.69
PC1	10	12688528**	68.8
PC2	8	4219765**	18.3
PC3	6	3036342**	9.9
PC4	4	1375528**	3.0
Error	72	253516.40	
Total	107	-	

*$p<0.05$; **$p<0.01$; DF, Degrees of freedom; MS, Mean sum of square; SS, Sum of square; PC, Principal component.

growing areas, which aligns with the current study (Table 3). Consequently, the substantial influence of seasons on grain yield is anticipated. This underscores the necessity of conducting trials across multiple environments to assess genotypic performance effectively. Suman *et al.* (2021) reported that the environment, genotype, and genotype-by-environment (G×E) interactions contributed 84%, 11%, and 3%, respectively to the total sum of squares for single-plant yield in rice, highlighting the predominant influence of environmental factors. Similarly, Kumar *et al.* (2020) observed significant environmental effects on days to 50% flowering in advanced breeding lines of red rice. In a separate study, Chen *et al.* (2025) found that the combined effects of genotype and genotype-by-environment interactions (G + G × E) accounted for 50.93% of the total phenotypic variation, emphasizing the importance of both genetic and interactive components in trait expression.

The highest sum of squares due to environments for grain yield explained that differences among seasonal means were very high justifying the application of stability models for genotypic evaluation. Present results are in harmony with the results of Krishna Murthy *et al.* (2021) and Rahman *et al.* (2025) for grain yield. Conversely, the mean sum of squares arising from genotype-environment interaction (GEI) surpassed both the genotypic and environmental effects, as observed by Sharifi *et al.* (2017) and Chen *et al.* (2025). Nevertheless, higher varietal effects were documented by Aktar *et al.* (2015) and Huang *et al.* (2021). The significant variation in environments affecting the days to 50% flowering may be attributed to short night temperatures (10-15°C), which extended the varietal period in the summer seasons (E_1 and E_3). Such short night temperatures are typically recorded during November, December, and January in Telangana, during rice nurseries and initial tillering stages can lead to physiological changes in rice, as discussed by De Los Reyes *et al.* (2003). Additionally, temperatures falling below the minimum requirement can also adversely impact fertility during the reproductive phase, consequently diminishing rice grain yield (Sato *et al.* 2011).

Principal component was decomposed into PC1, PC2, PC3 and PC4 for grain yield. PC1 and PC2 together explained about 87.1% of overall variation through axis 1 contributing 68.8% and axis 2 contributing 18.3%. The values for PC1 exceeded those of PC2, highlighting the greater impact of varieties on the overall sum of squares for grain yield. The biplot, illustrating the initial principal component axes capturing the majority of GEI variation is deemed ideal for elucidating GGE patterns (Yan *et al.* 2000). Here, the initial both principal components described about more than 85% of the G+GE sum of squares, achieving significant levels suggests that genotype-by-environment (G×E) interaction for the grain yield under investigation can be effectively captured and reliably predicted using

Table 3 Mean grain yield (kg/ha) of nine rice lines over four environments

Rice lines	Yield (kg/ha)					
	Environments				Mean yield (kg/ha)	Rank
	E_1	E_2	E_3	E_4		
G_1	9796	9082	8227	6685	8447	3
G_2	9211	9326	7676	4273	7621	6
G_3	10822	10272	8271	6715	9020	1
G_4	8215	6221	4355	4404	5799	9
G_5	10896	9335	7734	7280	8811	2
G_6	10782	8258	6992	6208	8060	5
G_7	10512	6856	8270	6957	8149	4
G_8	7170	8809	4026	4782	6197	8
G_9	10077	7665	7152	4317	7303	7
Mean	9720	8425	6967	5736	7712	

Details of the rice genotypes and environments are given in Table 1.

these two components. These outcomes align with the rice research conducted by Ponnuswamy *et al.* (2018).

Grain yield across environments ranged from 5,799–9,020 kg/ha, with a mean yield of 7,712 kg/ha. The highest yield was recorded for genotype G_3 (9,020 kg/ha), followed by G_5 (8,811 kg/ha) and G_2 (8,447 kg/ha), whereas the lowest yield was observed for G_4 (5,799 kg/ha). Within individual environments, grain yield varied from 7,170–10,896 kg/ha in E_1, 6,221–10,272 kg/ha in E_2, 4,355–8,271 kg/ha in E_3 and 4,273–7,280 kg/ha in E_4 (Table 3). The differential responses of rice genotypes, across varying environmental conditions, have been extensively evaluated in previous studies of Huang *et al.* (2021) and Chandramohan *et al.* (2023).

GGE Biplot-Genotype view for yield: Fig. 1A illustrated the genotypes based on their mean grain yield and stability across various environments. When the first principal component (PC1) comes close to the mean performance, the second principal component (PC2) should align closely with the genotype-by-environment (G × E) interaction, which serves as an indicator of instability. Consequently, G_7 and G_6, despite having above-average yields, exhibited little stability compared to their counterparts. In contrast, high-yielding varieties G_1, G_5, and G_9 demonstrated greater stability than others. The analysis also revealed that the distance between two varieties reflects their Euclidean distance, which quantifies their total divergence. In this context, G_3 and G_4 were found to be quite distinct, suggesting significant variances in mean grain yield or environmental interactions, while G_1 and G_5, as well as G_6 and G_7 were responded similarly and between them was proportional in all the environments for the expression of grain yield. Additionally, this biplot also depicts a virtual genotype that represents mean value across seasons. Thus, genotypes G_1, G_5, and G_6, which have higher yields and are positioned near the biplot origin, contributing minimally to both G and GE with lower PC1 scores. Conversely, genotypes G_4 and G_8 exhibited longer vector lengths, indicating substantial contributions to the genotype (G) main effect, the genotype-by-environment (GE) interaction, or both. G_3 and G_7 displayed relatively shorter vectors, their positions suggest potential for superior and inferior performance across environments, respectively. Notably, G_4 and G_8 were identified as the most unstable genotypes, reflecting greater variability in their responses.

An ideal line is characterized by high PC1 scores, indicating superior yield potential, and low PC2 scores, which signify enhanced stability (Yan *et al.* 2001). It is positioned close to the direction of the average environment, with its projection onto the AEC ordinate approaching zero. In addition, the representation of ideal line is depicted through concentric circles, where lines positioned closer to the center are deemed more advantageous than those located further away (Yan and Tinker 2006). In multiple environmental trials, the relative positions of varieties can change due to the prevalence of interactions (Parihar *et al.* 2017). As illustrated in Fig. 1B, the highest yielding genotype, G_3, is situated at the center of the concentric circles in an encouraging track, indicating its proximity to the ideal line in view of high yield and stability, in contrast to the other lines. G_5 and G_1 were identified as the second and third most desirable genotypes, respectively, because

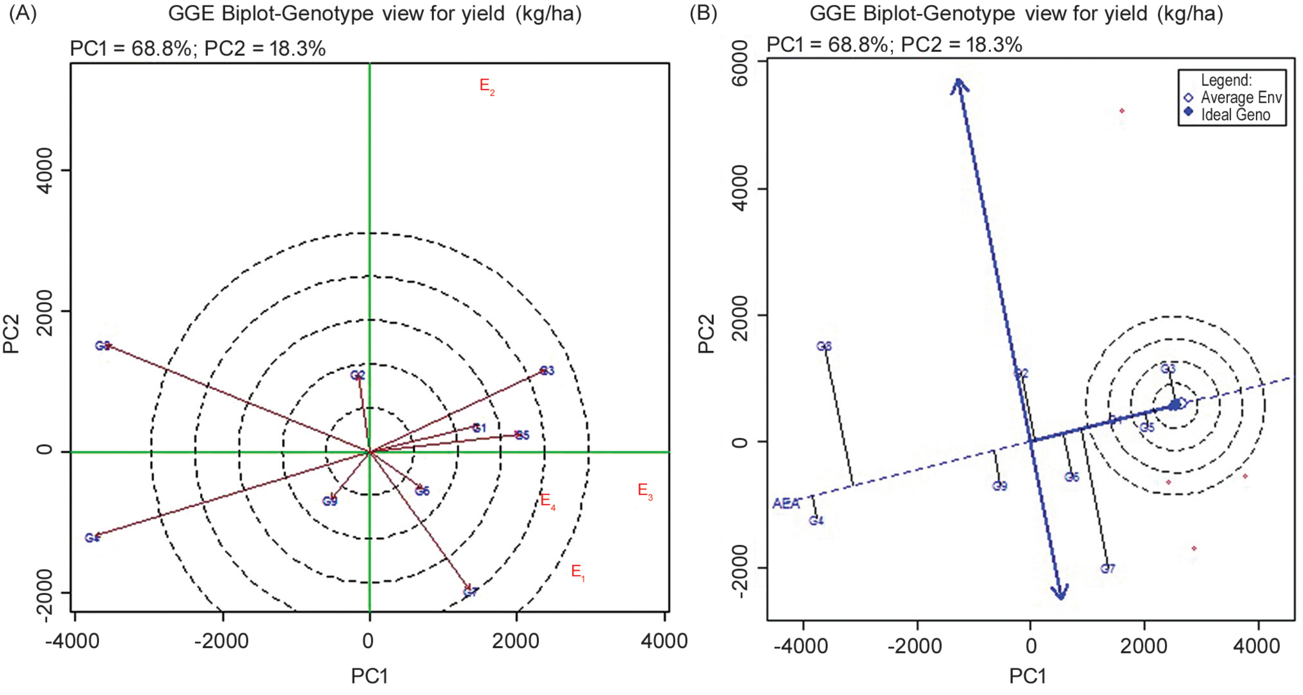

Fig. 1 (a) Biplot view ranks the lines according to their performance over the tested seasons for grain yield; (b) Biplot's average-environment coordination (AEC) view positions the lines in relation to ideal lines for grain yield.
Details of the rice genotypes and environments are given in Table 1.

of their proximity to the AEA, indicating their similarity to the ideal genotype. Similar findings were reported by Jain *et al.* (2019) in rice and Praveen *et al.* (2024) in groundnut regarding yield. Genotypes having shorter vector lengths recorded more stability, while those with lengthier vectors exhibit lower stability. Consequently, G_4 was identified as the least favourable genotype, consistently yielding below average, followed by G_9. On the other hand, lines G_8 and G_7 were considered as least stable since they had with longest vectors and their distant proximity to the AEA.

Polygon view of genotype-environment interaction for grain yield: The polygon representation of genotype-environment interaction concerning grain yield is crucial for assessing the potential presence of genotypes across various locations and determining the most suitable genotypes for particular environments. The visual depiction of "what-won-where" derived from multi-environment trial data is vital (Yan *et al.* 2000, Yan *et al.* 2001). The polygon effectively illustrates the interaction patterns between lines and environments, permitting for a complete interpretation of the biplot (Yan and Kang 2003). Given that different lines display varying performances across these locations, it becomes possible to pinpoint lines that are specifically adapted to each environment. This information is invaluable for breeders, enabling them to provide informed recommendations to farmers regarding the appropriate cultivars. This polygon is formed by connecting line segments between the most distant lines from the origin in the biplot, with these points at the vertices representing the highest or lowest yields in one or more locations. This structure aids in recognizing mega-environments and visualizing genotype-environment interactions (Yan and Tinker 2006). A mega-environment refers to a cultivation area with comparable situations that lead to nearly similar presentation among certain varieties (Gauch and Zobel 1996). In Fig. 2, four rays segment the biplot into four quadrants, with two of these quadrants representing two distinct mega-environments concerning grain yield. The vertex lines G_3, G_7, G_4, and G_8, positioned at the crests of this study, are the most distant to the origin and are anticipated to exhibit greater responsiveness. The line associated with a polygon vertex located in a region where environmental indicators were suppressed demonstrated superior performance under those specific environmental conditions. The first quadrant includes G_3, G_1 and G_5, with G_3 indicating a high-yielding winning line in mega-environment 1, which encompasses E_2, E_3, and E_4. The E_1, characterized by the presence of the winner genotype G_7 in conjunction with G_6 makes up another mega-environment. This outline advocates that the target environment can be effectively stratified into two distinct mega-environments, each favouring different genotypes for optimal yield performance. Similar findings have been reported in rice (El-Aty *et al.* 2024). In contrast, the other vertex genotypes, G_4 and G_8, showed lower yields and poorly adapted to four environments as these genotypes were situated in the two quadrants where no site-specific environmental indicators exhibited. On the other hand, lines G_1 and G_6 situated relatively close to the biplot origin were more stable across environments, achieving above-average mean, as they displayed an inferior responsiveness to seasonal variations compared to the vertex lines (Fig. 2).

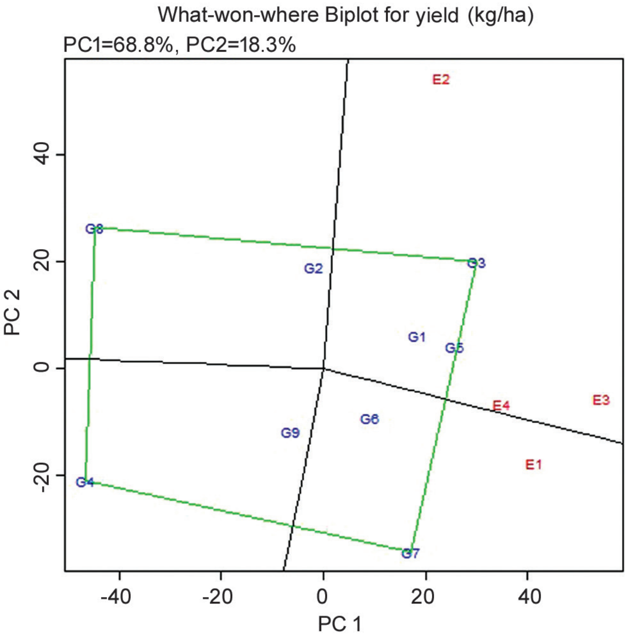

Fig. 2 Polygon view across four seasons for grain yield. Details of the rice genotypes and environments are given in Table 1.

The results of GGE biplot highlights that environmental factors are the predominant drivers to variation in rice grain yield, with genotypic effects playing a secondary role. In the GGE biplot genotype view, genotypes G_1 and G_5 were identified as high-yielding and stable. In the average environment coordination (AEC) view of the GGE biplot, G_3 followed by G_5 and G_1 were positioned at the centre of the concentric circles, indicating their closeness to the ideal genotype in terms of both high yield and stability. The polygon view revealed G_3 as the top performer in Mega-Environment 1 (E_2, E_3, E_4), and G_7 in a separate mega-environment (E_1) exhibiting both high yield potential and stability. GGE biplot has effectively demonstrated the utility of various biplots as robust tools, and current findings acknowledged following G_3, lines G_5 and G_1 emerged as most favourable options among the nine early-maturing rice genotypes, indicating their potential as donors for grain yield.

REFERENCES

Aktar A, Hasan M J, Kulsumu, Rahman M H, Khatun M and Islam M R. 2015. GGE biplot analysis for yield stability in multi-environment trials of promising hybrid rice (*Oryza sativa* L.). *Bangladesh Rice Journal* **19**(1): 1–8.

Atlin G N, McRae K B and Lu X. 2000. Genotype × Region interaction for two-row barley yield in Canada. *Crop Science* **40**: 1–6. https://doi.org/10.2135/cropsci2000.4011

Balakrishnan D, Malathi S, Venkateswara Rao Y, Krishnam Raju A, Sukumar M, Kavitha B and Sarla N. 2020. Detecting CSSLs and yield QTLs with additive, epistatic and QTL × environment interaction effects from *Oryza sativa* × *O. nivara* IRGC81832 cross. *Scientific Reports* **10**: 7766. https://doi.org/10.1038/s41598-020-64300-0

Bose L K, Jambhulkar N N, Pande K and Singh O N. 2014. Use of AMMI and other stability statistics in the simultaneous selection of rice genotypes for yield and stability under direct-seeded conditions. *Chilean Journal of Agricultural Research* **74**(1): 3–9. https://dx.doi.org/10.4067/S0718-58392014000100001

Bueno C S and Lafarge T. 2017. Maturity groups and growing seasons as key sources of variation to consider within breeding programmes for high yielding rice in the tropics. *Euphytica* **213**: 74. https://doi.org/10.1007/s10681-017-1862-z

Chandramohan Y, Krishna L, Srinivas B, Rukmini K, Sreedhar S, Prasad K S, Kishore N S, Rani C V D, Singh T V J and Jagadeeshwar R. 2023. Stability analysis of short duration rice genotypes in Telangana using AMMI and GGE bi-plot models. *Environment Conservation Journal* **24**(1): 243–52. https://doi.org/10.36953/ECJ.11952311

Chen R, Wang G, Yu J, Lu Y, Tao T, Wang Z, Hua Y, Li N, Wang H, Gharib A, Zhou Y, Xu Y, Li P, Xu C and Yang Z. 2025. Yield, stability, and adaptability of hybrid Japonica rice varieties in the East Coast of China. *Agronomy* **15**: 901.

De Los Reyes B G, Morsy M J, Gibbons, Varma T S N, Antoine W and Mc Grath J M. 2003. A snapshot of the low temperatures stress transcriptome of developing rice seedling (*Oryza sativa* L.) via ESTs from subtracted cDNA library. *Theoretical and Applied Genetics* **107**(6): 1071–82. https://doi.org/10.1007/s00122-003-1344-7

Department of Agriculture and Farmers Welfare. 2026. Unified Portal for Agricultural Statistics (UPAg): Rice Area, Production and Yield Statistics for 2024–25. Ministry of Agriculture and Farmers Welfare, Government of India, New Delhi. https://upag.gov.in

El-Aty M S A, Abo-Youssef M I, Sorour F A, Salem M, Gomma M A, Ibrahim O M, Yaghoubi Khanghahi M, Al-Qahtani W H, Abdel-Maksoud M A and El-Tahan A M. 2024. Performance and stability for grain yield and its components of some rice cultivars under various environments. *Agronomy* **14**: 2137. https://doi.org/10.3390/ agronomy14092137

Gauch H G and Zobel R W. 1996. AMMI analysis of yield trials. *Genotype-by-Environment Interaction*, pp. 85–122. Kang M S and Gauch H G (Eds). CRC Press, Boca Raton.

Gauch H G. 2006. Statistical analysis of yield trials by AMMI and GGE. *Crop Science* **46**: 1488–1500.

Gupta D K, Pramanick S and Singh A K. 2025. Long-term impact of aerosols and climate variability on rice yields across agroclimatic zones in India. *Earth Systems and Environment* **9**. https://doi.org/10.1007/s41748-025-00701-3

Hori K, Matsubara K and Yano M. 2016. Genetic control of flowering time in rice: Integration of Mendelian genetics and genomics. *Theoretical and Applied Genetics* **129**(12): 2241–52.

Huang M, Qi-Yuan T, He-Jum A and Ying-Bin Z. 2017. Yield potential and stability in super hybrid rice and its production strategies. *Journal of Integrative Agriculture* **16**(5): 1009–17. https://doi.org/10.1016/S2095-3119(16)61535-6

Huang X, Jang S, Kim B, Piao Z, Redona E and Koh H J. 2021. Evaluating genotype × environment interactions of yield traits and adaptability in rice cultivars grown under temperate, subtropical and tropical environments. *Agriculture* **11**(6): 558. https:// doi.org/10.3390/agriculture11060558

Jain B T, Sarial A K and Kaushik P. 2019. Understanding G × E interaction of elite basmati rice (*Oryza sativa* L.) genotypes under north Indian condition using stability models. *Applied Ecology and Environmental Research* **17**(3): 5863–85. https://doi.org/10.15666/aeer/1703_58635885

Kang M S. 1993. Simultaneous selection for yield and stability in crop performance trials: Consequences for growers. *Agronomy Journal* **85**(3): 754–57. https://doi.org/10.2134/agronj1993.00021962008500030042x

Kesh H, Kharb R, Ram K, Munjal R, Kaushik P and Kumar D. 2021. Adaptability and AMMI biplot analysis for yield and agronomical traits in scented rice genotypes under diverse production environments. *Indian Journal of Traditional Knowledge* **20**(2): 550–62.

Krishnamurthy S L, Sharma P C, Sharma D K, Singh Y P, Mishra V K, Burman D, Maji B, Mandal S, Sarangi S K, Gautam R K, Singh P K, Manohara K K, Marandi B C, Chattopadhyay K, Padmavathi G, Vanve P B, Patil K D, Thirumeni S, Verma O P, Khan A H, Tiwari S, Geetha S, Gill R, Yadav V K, Roy B, Prakash M, Anandan A, Bonifacio J, Ismail A M and Singh R K. 2021. Additive main effects and multiplicative interaction analyses of yield performance in rice genotypes for general and specific adaptation to salt stress in locations in India. *Euphytica* **217**: 20. https://doi.org/10.1007/s10681-020-02730-7

Kumar B M D, Purushottam A P, Raghavendra P, Vittal T, Shubha K N and Madhuri R. 2020. Genotype environment interaction and stability for yield and its components in advanced breeding lines of red rice (*Oryza Sativa* L.). *Bangladesh Journal of Botany* **49**(3): 425–35.

Liang Z, Menjivar J R, Zhang L, Zhang J and Shen X. 2024. Examining the effects of adopting early maturing crop varieties on agricultural productivity, climate change adaptation, and mitigation. *International Journal of Low-Carbon Technologies* **19**: 1256–74. https://doi.org/10.1093/ijlct/ctad150

Parihar A K, Basandrai A K, Sirari A, Dinakaran D, Singh D, Kannan K, Kushawaha P S, Adinarayan M, Akram M, Latha T K S, Paranidharan V and Gupta S. 2017. Assessment of mungbean genotypes for durable resistance to Yellow Mosaic Disease: Genotype × Environment interaction. *Plant Breeding* **136**(1): 94–100. https://doi.org/10.1111/pbr.12446

Poli Y, Balakrishnan D, Desiraju S, Panigrahy M, Voleti S R, Mangrauthia S K and Neelamraju S. 2018. Genotype × Environment interactions of Nagina22 rice mutants for yield traits under low phosphorus, water limited and normal irrigated conditions. *Scientific Reports* **8**(1): 15530. https://doi.org/10.1038/s41598-018-33812-1

Ponnuswamy R, Rathore A, Vemula A, Das R R, Singh A K and Balakrishnan D. 2018. Analysis of multi-location data of hybrids rice trials reveals complex genotype by environment interaction. *Cereal Research Communications* **46**(1): 146–57. https://doi.org/10.1556/0806.45.2017.065

Praveen K, Ajay B C, Gangadhara K, Kumar N, Choudhary R R, Mahatma M K, Singh S, Reddy K K, Bera S K, Sangh C H, Rani K, Chavada Z and Solanki K D. 2024. AMMI and GGE biplot analysis of genotype by environment interaction for yield and yield contributing traits in confectionery groundnut. *Scientific Reports* **14**: 2943. https://doi.org/10.1038/s41598-024-52938-z

Rahman A U, Akhtar M, Shah S M A, Shah M A, Arif M, Khan W, Rasheed S M, Davide L C and Khan S. 2025. Application of GGE biplot analysis for assessing stability in recombinant inbred lines (RILs) of rice (*Oryza sativa* L.). *Indian Journal of Genetics and Plant Breeding* **85**(1): 237–42.

Sackey O K, Feng N, Mohammed Y Z, Dzou C F, Zheng D, Zhao L and Shen X. 2025. A comprehensive review on rice responses and tolerance to salt stress. *Frontiers in Plant Science* **16**: 1561280. https://doi.10.3389/fpls.2025.1561280

Sato Y, Masuta Y, Saito K, Murayama S and Ozawa K. 2011. Enhanced chilling tolerance at the booting stage in rice by transgenic overexpression of the ascorbate peroxidase gene, *OsAPXa*. *Plant Cell Reports* **30**(3): 399–406. https://doi.org/10.1007/s00299-010-0985-7

Seck F, Covarrubias-Pazaran G and Gueye T. 2023. Realized genetic gain in rice: Achievements from breeding programs. *Rice* **16**: 61. https://doi.org/10.1186/s12284-023-00677-6

Senguttuvel P, Sravanraju N, Jaldhani V, Divya B, Beulah P, Nagaraju P, Manasa Y, Prasad A S H, Brajendra P, Gireesh C, Anantha M S, Suneetha K, Sundaram R M, Madhav M S, Tuti M D, Subbarao L V, Neeraja C N, Bhadana V P, Rao P R, Voleti S R and Subrahmanyam D. 2021. Evaluation of genotype by environment interaction and adaptability in lowland irrigated rice hybrids for grain yield under high temperature. *Scientific Reports* **11**(1): 15825. https://doi.org/10.1038/s41598-021-95264-4

Sharifi P, Aminpanah H, Erfani R, Mohaddesi A and Abbasian A. 2017. Evaluation of genotype × environment interaction in rice based on AMMI model in Iran. *Rice Science* **24**(3): 173–80. https://doi.org/10.1016/j.rsci.2017.02.001

Suman K, Neeraja C N, Madhubabu P, Rathod S, Bej S, Jadhav K P, Kumar J A, Chaitanya U, Pawar S C, Rani S H, Subbarao L V and Voleti S R. 2021. Identification of promising RILS for high grain zinc through genotype × environment analysis and stable grain zinc QTL using SSRs and SNPs in rice (*Oryza sativa* L.). *Frontiers in Plant Science* **12**: 587482. https://doi.org/10.3389/fpls.2021.587482

Yan W, Hunt L A, Sheng Q and Szlavnics Z. 2000. Cultivar evaluation and mega environment investigation based on the GGE biplot. *Crop science* **40**(3): 597–605. https://doi.org/10.2135/cropsci2000.403597x

Yan W, Cornelius P L, Crossa J and Hunt L A. 2001. Two types of GGE biplots for analyzing multi-environment trial data. *Crop Science* **41**: 656–63. https://doi.org/10.2135/cropsci2001.413656x

Yan W and Kang M S. 2003. *GGE Biplot Analysis: A Graphical Tool for Breeders, Geneticists and Agronomists*, pp. 1–267. Yan W and Kang M S (Eds). CRC Press LLC, Boca Raton, Florida.

Yan W and Tinker N A. 2006. Biplot analysis of multi-environment trial data: Principles and applications. *Canadian Journal of Plant Science* **86**: 623–45. https://doi.org/10.4141/P05-169

Zhou S, Zhu S, Cui S, Hou H, Wu H, Hao B, Cai L, Xu Z, Liu L, Jiang L, Wang H and Wan J. 2021. Transcriptional and post-transcriptional regulation of heading date in rice. *New Phytol* **230**: 943–56.