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TOWARDS CLIMATE RESILIENT RICE: STABILITY ANALYSIS OF GRAIN YIELD ACROSS MULTI-ENVIRONMENTS IN CHHATTISGARH USING THE EBERHART AND RUSSELL MODEL

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ABSTRACT

Ensuring stable rice production under variable environments is one of the greatest challenges for global food security. Genotype × environment (G×E) interactions often limit the identification of high-yielding and widely adaptable cultivars. To address this, the present investigation was conducted during *Kharif* 2024 across six locations of Indira Gandhi Krishi Vishwavidyalaya in Chhattisgarh—Raipur, Ambikapur, Bilaspur, Jagdalpur, Kawardha and Raigarh. A total of 42 rice genotypes, including 9 checks, were evaluated in a randomized block design with three replications for grain yield (kg/ha). Stability analysis was performed using the Eberhart and Russell model. Significant G×E interactions were observed for grain yield, indicating strong environmental influence on genotype performance. R-2322-180-1-169-1, IR18A1061, IR17A3050 and CR-Dhan-310 genotypes demonstrated high mean yield, regression coefficients near unity, and low deviations from regression, reflecting wide adaptability and stability across environments. Other genotypes expressed specific adaptability to either favorable or stress-prone locations, offering targeted potential for region-specific varietal improvement. This study provides one of the most comprehensive multi-environment stability assessments of rice genotypes in Chhattisgarh, reinforcing the continued relevance of the Eberhart and Russell model in modern breeding. The findings deliver actionable insights for climate-resilient rice improvement, ensuring sustainable yield stability in Chhattisgarh and contributing to food security at both regional and national levels.

***Key words*:** Rice, stability analysis, GxE interaction, Eberhert-Russell model and stable genotypes.

Introduction

Rice *(Oryza sativa* L.) is the primary staple food for more than half of the global population and plays a pivotal role in food and nutritional security (FAO, 2024). India, the world's second-largest rice producer, reported a projected output of 119.93 million tonnes during *Kharif* 2024–25, highlighting its agricultural significance (Government of India, 2024). Within India, Chhattisgarh often referred to as the "Rice Bowl of India" is a major contributor, with rice productivity increasing from 2,134 kg/ha in 2022 to 2,602 kg/ha in 2023 (CEIC Data, 2024).

Since grain yield is a polygenically controlled trait and highly influenced by genotype × environment (G × E) interactions, such interactions often obscure the true genetic potential of genotypes and complicate selection strategies (Crossa, 1990). High-yielding varieties often display greater sensitivity to environmental changes, while highly stable genotypes may compromise yield potential (Becker and Leon, 1988). Thus, balancing yield performance with stability is key to achieving resilience in rice cultivation under variable climates such as those of Chhattisgarh. To address this challenge, the Eberhart and Russell (1966) regression model provides a robust framework for identifying stable genotypes. According to this model, a desirable genotype is characterized by high mean yield, a regression coefficient near unity (bi = 1), and negligible deviation ($S^2_{di} \approx 0$), indicating predictable and stable performance (Bose *et al*., 2014; Purchase *et al*., 2000). It partitions G×E into predictable (regression coefficient, b_i) and unpredictable (deviation from regression, S^2_{di}) components (Eberhart & Russell, 1966; Lin *et al*., 1986). Such analytical approaches are crucial for climate-resilient breeding, as they allow breeders to distinguish between genotypes that are broadly adapted and those better suited to specific environments.

Considering the increasing climate variability in Chhattisgarh, identifying climate-resilient and stable rice genotypes is critical. For a diverse rice-growing state like Chhattisgarh, characterized by three agro-climatic zones and considerable seasonal variability, this model is highly relevant. It provides a scientific basis to identify genotypes that can perform reliably under variable rainfall, soil fertility, and management conditions. For instance, genotypes with bi ≈ 1 and $S^2_{di} \approx 0$ would be recommended for widespread cultivation across the state, while those with bi < 1 may be targeted for stress-prone or low-input regions, and bi > 1 genotypes could be deployed in favorable, irrigated, or high-input zones. Thus, the Eberhart and Russell model not only aids in varietal selection but also supports region-specific genotype recommendations to strengthen climate-resilient rice breeding programs in Chhattisgarh. The findings from this research are expected to provide valuable insights into selecting stable and high-yielding rice genotypes for Chhattisgarh, with broader implications for ensuring sustainable rice production in India under climate variability.

Materials and Methods

The present investigation was conducted during *Kharif* 2024 across six locations of three major agro-ecological zones of Chhattisgarh-: Raipur, Ambikapur, Bilaspur, Jagdalpur, Kawardha and Raigarh. A total of 42 rice genotypes, including nine checks (Table 1), were evaluated to assess yield performance and stability. The trials were laid out in a Randomized Block Design (RBD) with three replications at each location. Standard agronomic practices recommended for the region were followed to ensure optimal crop growth. Grain yield (kg ha^{-1}) was recorded from each plot and converted to yield per hectare. Location-wise mean yield was used for stability analysis. Considering the increasing climate variability in Chhattisgarh, the stability of genotypes was assessed using the Eberhart and Russell (1966) model. The model partitions genotype × environment (G×E) interaction into a linear component (bi) representing environmental response and a deviation from regression (S^2di) representing unpredictability.

Results and Discussion

Developing climate-resilient rice requires the identification of genotypes that not only deliver high productivity but also exhibit stability across diverse agro-ecological conditions. Stability analysis in rice breeding is therefore indispensable, as it allows breeders to select

Table 1: List of experimental material.

S.	Genotypes	S.	Genotypes
1	IR17A2891	22	IR18A1073
2	IR17A2769	23	IR18A1072
3	R-2322-180-1-169-1	24	R2759-20-1
4	R2739-86-1	25	R-2297-4-1-2-1
5	R-2300-377-2-261-1	26	R-1877-41-1-13-1
6	**Protezin(ch)**	27	IR17A3105
7	IR18A1061	28	**PAC- 807 (HyCh)**
8	IR17A3050	29	R-2321-154-1-94-1
9	R-2775-C6-2-3	30	**Narendra 97(ch)**
10	JDP-1212	31	R-2341-281-2-332-1
11	R2744-119-1	32	R-RHZ-MI-95
12	**Samleshwari(ch)**	33	R-2774-C-3-1-1
13	R2744-19-1	34	IR18A1068
14	**Danteshwari(ch)**	35	R-2341-337-3-180-1
15	CR-Dhan-310	36	US 316
16	IR18A1423	37	R-1670-3269-2-3926
17	R2756-27-1	38	JDP-2018
18	**Sahbhagi Dhan-1(ch)**	39	**Vandana(ch)**
19	**Bastar Dhan-1(ch)**	40	**Annada(ch)**
20	R-2307-46-1-24-1	41	SDSR-1001
21	JDP-5925	42	SDSR-1006

Table 2: Pooled analysis of variance for stability of grain yield kg per hectare.

Source	DF	Mean Squares
Genotype	41	966960.61**
Environment	5	346434676.006**
Genotype × Environment	205	564467.18**
Env + Genotype × Environment	210	3300508.95
Environment (Linear)	1	577391089.74**
Environment × Genotype (Lin)	41	828954.2865*
Pooled Deviation	168	486480.02**
Pooled Error	492	259661.77
Total	251	
(*) at 5% probability and (**) at 1% probability		

Table 3: Ranking (Environment Index) of location according to index value and mean of yield kg per hectare.

Rank	Environments	Mean	Index Value
I	Jagdalpur (E4)	5846.69	2359.87
II	Raipur(E1)	5333.67	1846.85
III	Ambikapur (E2)	2753.58	-733.22
IV	Kawardha (E5)	2532.88	-953.93
V	Raigarh (E6)	2497.05	-989.76
VI	Bilaspur(E3)	1957.01	-1529.8

Table 4: Estimation of different stability parameters for grain yield.

Genotype	Grain Yield (Mean)	Reg Coefficient(b_i)	Stability Parameter (S^2_{di})	Deviation (sd)
JDP-1212	4210.45	1.25	961442.21**	0.305
IR18A1072	4187.25	1.45	863825.34 **	0.277
R2756-27-1	4186.64	1.1	456882.72 **	0.158
IR18A1068	4056.46	1.51	554739.60 **	0.187
R-2322-180-1-169-1	4003.45	1.08	91270.47	0.052
SDSR-1001	3838.45	0.90	645760.20 **	0.213
IR18A1061	3829.78	0.91	105500.72	0.056
R-1877-41-1-13-1	3824.37	0.97	464956.47 **	0.16
IR17A2891	3809.06	1.12	392575.40 **	0.138
Samleshwari(ch)	3803.85	0.99	1203249.41 **	0.375
IR18A1073	3781.79	0.83	547494.17 **	0.184
IR17A2769	3774.11	0.94	163611.64 *	0.073
IR17A3050	3761.97	1.11	70961.64	0.046
Bastar Dhan-1(ch)	3717.41	1.30	531644.70 **	0.18
JDP-2018	3668.77	0.88	163105.43 *	0.073
CR-Dhan-310	3646.78	1.06	100062.28	0.054
US 316	3641.60	1.38	357855.05 **	0.129
R2744-119-1	3566.22	0.98	839497.90 **	0.268
IR18A1423	3564.26	1.16	197130.74 *	0.083
Narendra-97(ch)	3548.97	0.95	226091.78 **	0.091
PAC - 807 (HyCh)	3541.35	0.83	251809.81 **	0.098
Protezin(ch)	3485.01	1.14	54247.17	0.041
R-2300-377-2-261-1	3447.59	1.28	1529762.03 **	0.47
R-2341-337-3-180-1	3389.41	1.19	-47047.23	0.011
Sahbhagi Dhan-1(ch)	3356.05	0.69	1788811.07 **	0.546
IR17A3105	3298.41	1.05	219703.61 **	0.089
R2759-20-1	3293.44	0.92	290746.20 **	0.11
JDP-5925	3285.90	1.08	164043.93 *	0.073
Danteshwari(ch)	3282.82	0.84	353675.62 **	0.128
R2744-19-1	3265.42	1.18	13314.62	0.029
R-2775-C6-2-3	3242.37	1.02	145224.57 *	0.067
R-2307-46-1-24-1	3219.53	0.68	272503.79 **	0.104
R-1670-3269-2-3926	3212.29	1.06	259535.47 **	0.101
R2739-86-1	3203.81	0.85	17041.32	0.03
R-2774-C-3-1-1	3132.87	1.15	-40412.37	0.013
R-2321-154-1-94-1	3116.32	0.96	381620.95 **	0.138
SDSR-1006	3090.26	0.58	613909.29 **	0.204
R-2297-4-1-2-1	3086.73	0.69	332861.72 **	0.122
R-2341-281-2-332-1	3083.54	1.11	155883.59 *	0.071
R-RHZ-MI-95	3036.17	0.87	67173.96	0.045
Annada(ch)	2636.95	0.53	-22863.63	0.019
Vandana(ch)	2318.13	0.25	1057688.39 **	0.333
Pooled Mean	**3486.81**			

genotypes that consistently perform despite fluctuations in environmental conditions (Kumar *et al.*, 2020; Anandan *et al.*, 2009). Prior to pooling the data, Bartlett's test of homogeneity of error variances was conducted. The test result was significant, indicating heterogeneity of variances among environments. This suggested that models assuming homogeneity would not be appropriate for analyzing G × E interactions. To address this, the Eberhart and Russell model was employed, as it accommodates unequal variances and provides reliable insights into genotype stability and adaptability.

The pooled analysis of variance (ANOVA) across six environments revealed highly significant effects of environment, genotype, and genotype × environment

Table 5: Classification of genotypes based on the mean performance and regression coefficient (b_i) values across diverse environments.

S.	Environment	Remark	Genotypes
1.	Jagdalpur (E4) Raipur (E1)	Favourable	R-2322-180-1-169-1, IR18A1061, IR17A3050, CR-Dhan-310, Protezin, R2744-19-1, R-2774-C-3-1-1, R-2341 337-3-180-1
2.	Ambikapur(E2) Kawardha (E5) Raigarh (E6) Bilaspur (E3)	Unfavourable	R-2322-180-1-169-1, IR18A1061, IR17A3050CR-Dhan-310, Annada, R273986-1, R-RHZ-MI-95

(G×E) interaction for grain yield (Table 2). This indicates meaningful differential responses of the 42 rice genotypes across locations, consistent with previous MET-based findings (Das *et al.*, 2024). The significant environment (linear) effect confirmed strong differences among locations, while the G×E (linear) component showed that differences in genotype responses were predictable. The significant pooled deviation further highlighted the presence of non-linear interactions, reflecting unpredictable environmental influences. These results highlight that genotype performance for grain yield was partly predictable and partly unpredictable, in agreement with earlier studies (Ghrilahre and Sarial, 2011; Krismawati *et al.*, 2013; Jain *et al.*, 2018). The significance of both linear and non-linear components validates the application of the Eberhart and Russell (1966) stability model, which effectively distinguishes genotypes with general adaptability ($bi \approx 1$, $S^2_{di} \approx 0$) from those with specific adaptation to certain environments. Thus, the combined ANOVA not only confirms the presence of strong G×E interactions but also provides a reliable basis for stability analysis, critical for identifying climate-resilient and location-suited rice genotypes for Chhattisgarh.

The environmental index reflects the favorability of an environment for genotype performance. According to Breeze (1969), it serves as a useful measure for identifying locations that support the maximum expression of genetic potential. In the present study, Jagdalpur (E4; 5,846.69 kg/ha) and Raipur (E1; 5,333.67 kg/ha) recorded positive environmental indices, classifying them as favourable or "rich" environments. In contrast, Ambikapur (E2), Bilaspur (E3), Kawardha (E5), and Raigarh (E6) exhibited negative indices, indicating "poor" or stressful environments, likely due to factors such as drought or low soil fertility.

The evaluation of 42 rice genotypes across six environments of Chhattisgarh revealed significant variation in mean grain yield, ranging from 2318.13 kg/ha (Vandana) to 4210.45 kg/ha (JDP-1212). Notably, 21 genotypes recorded higher-than-average mean yields per hectare, suggesting their potential for direct cultivation or use in breeding programs targeting enhanced productivity.

Stability analysis using the Eberhart and Russell (1966) model identified distinct groups of genotypes based on adaptability. A first group of genotypes exhibited $bi \approx 1$ with non-significant S^2_{di}, reflecting wide adaptability and stable performance across environments. Notably, R-2322-180-1-169-1 (4003.45 kg/ha), IR18A1061 (3829.78 kg/ha), IR17A3050 (3761.97 kg/ha) and CR-Dhan-310 (3646.79 kg/ha) demonstrated both high mean yields and stability, making them promising candidates for multi-location trials and varietal release in Chhattisgarh's diverse agro-climatic zones. Their performance aligns with earlier reports (Crossa, 1990; Shukla, 2004), which emphasized that genotypes with bi close to unity and low S^2_{di} values are most suited for general adaptation.

A second group comprised genotypes with $bi > 1$ and non-significant S^2_{di}, indicating high responsiveness to favorable environments such as Jagdalpur (E4) and Raipur (E1). Genotypes like Protezin, R-2744-19-1, R-2774-C-3-1-1 and R-2341-337-3-180-1 responded well under rich environments but had lower absolute yield potential. These findings suggest their greater utility in breeding programs for responsiveness traits rather than direct release under high-input systems in Chhattisgarh. Conversely, a third group showed $bi < 1$ with non-significant S^2_{di}, reflecting lower responsiveness but better adaptation to unfavorable or stress-prone environments such as Ambikapur (E2), Bilaspur (E3), Kawardha (E5) and Raigarh (E6). Genotypes including Annada (2636.95 kg/ha), R-2739-86-1 (3203.81 kg/ha) and R-RHZ-MI-95 (3036.17 kg/ha), though relatively low-yielding, were stable under adverse conditions. Such genotypes are suitable for low-input and marginal areas and serve as valuable donors of stability and stress-resilience traits for rice improvement programs in Chhattisgarh.

Conclusion

Overall, the study on 42 rice genotypes across six diverse environments of Chhattisgarh revealed significant genotype × environment interactions, underscoring the importance of stability analysis for identifying widely adaptable as well as location-specific varieties. Genotypes such as R-2322-180-1-169-1, IR18A1061, IR17A3050, and CR-Dhan-310 demonstrated high yield stability and wide adaptability, while others like Protezin, R-2744-19-1, R-2774-C-3-1-1, and R-2341-337-3-180-1 were highly responsive to favorable environments such as Jagdalpur and Raipur. In contrast, stress-resilient genotypes such as Annada, R2739-86-1, and R-RHZ-MI-95 showed suitability for marginal locations like Ambikapur, Bilaspur, Kawardha and Raigarh.

Importantly, this study highlights that stability analysis is not only a tool for yield evaluation but also a strength for climate-resilient rice breeding programs. By distinguishing genotypes with wide adaptability from those suited to stress-prone environments, it provides a scientific basis for developing varieties that can withstand climate variability, an urgent requirement under the changing agro-climatic scenarios of Chhattisgarh. Thus, the study not only identifies stable, high-yielding genotypes but also contributes to the long-term goal of sustainable and climate-resilient rice improvement in Chhattisgarh, ensuring food and livelihood security for farmers under variable environments.

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