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RECONFIGURING RICE PRODUCTION UNDER COMPOUND CLIMATE EXTREMES: GENOTYPIC VARIATION IN YIELD STABILITY, RESOURCE-USE EFFICIENCY, AND ADAPTIVE RESPONSES UNDER HUMID SUBTROPICAL CONDITIONS

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ABSTRACT

Rice genotypes often respond differently when heat and water-related stresses occur together, and these differences can lead to considerable variation in yield stability between seasons. This study evaluated genotypic variation and yield stability of twelve rice genotypes under contrasting reference, heat–moisture-deficit and excess-moisture environments during the 2022 and 2023 kharif seasons at KVK Dhalai, Tripura, India. The genotypes were evaluated in a randomized complete block design with four replications across six year × environment combinations. Environment strongly influenced grain yield: pooled mean yield was approximately 5.60 t ha^{-1} under reference conditions, 4.05 t ha^{-1} under heat–moisture deficit and 4.92 t ha^{-1} under excess moisture. Across environments, mean yield ranged from 4.46 t ha^{-1} in Swarna to 5.26 t ha^{-1} in CR Dhan 802. CR Dhan 802 (5.26 t ha^{-1}), CR Dhan 801 (5.19 t ha^{-1}), Gomati Dhan (5.12 t ha^{-1}) and Tripura Chikan Dhan (5.09 t ha^{-1}) recorded comparatively high mean yields. Sahbhagi Dhan showed the lowest yield variability (CV 8.8%) and retained 84% of its reference yield under heat–moisture deficit, whereas Swarna-Sub1 and Ranjit-Sub1 retained 96% and 92% of reference yield, respectively, under excess moisture. Grain yield showed GCV and PCV values of 6.8 and 8.8%, respectively, with an entry-mean broad-sense heritability of 70.9%. Combined analysis indicated significant effects of genotype and genotype × environment interaction on grain yield. Overall, the genotypes differed appreciably in productivity, response to stress and yield stability, highlighting the value of evaluation across contrasting environments when selecting rice material for variable climatic conditions.

KEYWORDS: Oryza sativa L.; genotype × environment interaction; yield stability; drought; heat stress; excess moisture; heritability

1. INTRODUCTION

Rice (Oryza sativa L.) supports the food security of a large share of the global population and remains the dominant staple across much of South and Southeast Asia. With a changing climate, rice crops are increasingly exposed to more than one stress at a time rather than to isolated stress events. In rice, heat and drought frequently co-occur because high evaporative demand accelerates soil-water depletion, while monsoon systems can alternate rapidly between dry spells and intense rainfall. Reviews of combined heat–drought stress emphasize that the joint response cannot always be predicted from single-stress experiments because reproductive development, photosynthesis, water relations and grain filling respond non-linearly to simultaneous stress (Lawas et al., 2018; Zandalinas et al., 2021; Fahad et al., 2022). A recent systematic review further highlighted the importance of genetic and molecular regulation of heat and drought tolerance in rice and the need to integrate field phenotyping with genetic improvement (Fahad et al., 2022) (Debnath et al., 2026b).

The reproductive stage is particularly vulnerable to high temperature. Jagadish et al. (2007) demonstrated marked reductions in spikelet fertility when rice experienced high temperature around anthesis, with response depending on both temperature and exposure duration. Peng et al. (2004) reported declining rice yield with increasing night temperature in tropical field observations, while Welch et al. (2010) found that minimum and maximum temperatures can have opposing effects on Asian rice yields. Tiwari et al. (2021), evaluating rice hybrids under contrasting thermal environments, found significant genotype × environment interaction and identified spikelet fertility as one of the traits most affected by high temperature. These findings also show why temperature during the actual flowering period of each genotype is more informative than a seasonal temperature average.

Drought is equally important in rainfed eastern India. Kumar et al. (2012) evaluated rice genotypes across favorable, moderate-drought and severe-drought environments and showed that high yield and stability can be combined through multi-environment selection. Sahbhagi Dhan is a prominent example of such breeding progress. Anantha et al. (2016) reported that Sahbhagi Dhan possesses several traits associated with drought performance, including high harvest index under stress and useful yield stability across wet-season environments. Large-scale evidence from eastern India subsequently showed that Sahbhagi Dhan often maintained a yield advantage over farmer varieties during drought years and could also perform competitively under non-drought conditions (Kumar et al., 2020). ICAR documentation describes Sahbhagi Dhan as a short-duration drought-tolerant variety capable of yielding approximately 3.8–4.5 t ha^{-1} under suitable conditions (ICAR, 2010).

Excess water presents a very different physiological challenge to the rice plant. Complete submergence restricts gas exchange, depletes carbohydrate reserves and can cause severe mortality in susceptible rice. The SUB1 quantitative trait locus on chromosome 9 has been successfully introgressed into widely grown rice backgrounds through marker-assisted backcrossing. Singh et al. (2009) showed that SUB1 introgression improved field performance after submergence in popular rice backgrounds, while Mackill et al. (2012) reviewed the development and rapid dissemination of Sub1 varieties. Genetic gains observed in Indian rainfed systems have also demonstrated yield advantages of Swarna-Sub1 over farmer-grown lowland varieties (Kumar et al., 2020). These findings provide a strong basis for including Swarna-Sub1 and Ranjit-Sub1 as excess-water comparators.

CR Dhan 801 and CR Dhan 802 are particularly relevant to this evaluation because both were developed for production environments affected by more than one type of water-related stress. ICAR-NRRI describes CR Dhan 801 (IET 25667) as a climate-smart rice variety derived from IR81896-B-B-195/2*Swarna-Sub1//IR91659-54-35, with approximately 6.3 t ha^{-1} yield under normal conditions, 4.0 t ha^{-1} under submergence and 2.9 t ha^{-1} under drought. CR Dhan 802 (Subhas; IET 25673) was developed from Swarna-Sub1*4/IR81896-B-B-195 and was also targeted to drought- and submergence-prone shallow lowlands (ICAR-NRRI, 2019). Their pedigrees and stress-targeted development make them more informative for a genetics-oriented study than a panel composed only of conventional high-yielding varieties.

Adaptation to local growing conditions is equally important. Tripura Chikan Dhan (TRC 2008-4/IET 22112) has been promoted for Tripura, with ICAR documentation reporting yields around 5.6–5.8 t ha^{-1} and an average yield advantage of about 15% over comparison varieties in frontline demonstrations conducted across several Tripura districts during 2010–2013 (ICAR, 2020). Khowai (TRC 2005-3) has likewise been reported at approximately 5.6–5.8 t ha^{-1} with yield advantages over Swarna and MTU 1010 in Tripura demonstrations (ICAR, 2020). Such published benchmarks are not substitutes for local experimental observations, but they provide a defensible biological context for genotype selection and for checking whether field means fall within plausible ranges.

Yield stability is a quantitative trait that is strongly influenced by genotype × environment interaction. Genotype × environment interaction changes the relative performance of genotypes across environments and can obscure selection based on simple means. Finlay and Wilkinson (1963) and Eberhart and Russell (1966) developed classical stability concepts, while AMMI and GGE biplot methods provide multivariate approaches to visualize main effects and interaction structure (Gauch, 1992; Yan et al., 2000; Yan and Kang, 2003). In rice, Tiwari et al. (2021) demonstrated the value of AMMI and GGE approaches under high-temperature environments. More recent rice research continues to integrate AMMI, GGE and multivariate tools for yield-stability interpretation (Veeraraj et al., 2026) (Debnath et al., 2026c).

Variance components, genotypic coefficient of variation (GCV), phenotypic coefficient of variation (PCV) and broad-sense heritability provide additional information on the repeatability of genotype differences. Rice variability studies commonly report PCV values exceeding GCV because phenotypic variation includes both genetic and environmental components (Tiwari et al., 2019). Together, these parameters help describe how consistently cultivar differences are expressed across environments. Field-derived variance components, however, represent quantitative-genetic evidence and should not be described as molecular evidence unless DNA-level data are generated.

Against this background, twelve rice genotypes were evaluated at KVK Dhalai, Tripura, to examine variation in yield, stress response and yield stability under contrasting managed environments. The objectives were to (i) quantify genotype differences in grain yield and major yield-related traits; (ii) compare yield retention under heat–moisture-deficit and excess-moisture conditions; (iii) characterize cross-environment yield stability and resource-use responses; and (iv) partition genotype, year, environment and genotype × environment variation using quantitative-genetic statistics. It was hypothesized that the genotypes would differ not only in average productivity but also in their ability to maintain yield as temperature and water conditions changed.

2. MATERIALS AND METHODS

2.1 Experimental site and agroclimatic setting

The study was conducted in the Experimental Farm of KVK Dhalai, Salema, Dhalai District, Tripura, India, in the humid subtropical north-eastern hill region. KVK Dhalai farm is located at 23.92° N and 91.90° E and is about 120 m above mean sea level. The experiment covered the kharif seasons of 2022 and 2023. Daily maximum and minimum temperature, rainfall, relative humidity, sunshine/solar radiation and, evapotranspiration are taken from the KVK automatic weather station. Stage-wise summaries is followed crop phenology because rice responses to heat and water stress are strongly stage-dependent (Jagadish et al., 2007; Wassmann et al., 2009; Tiwari et al., 2021). Root-zone moisture or water potential was measured directly in drought treatments, while standing-water depth and duration was recorded in excess-water treatments, consistent with the distinction between drought, waterlogging, stagnant flooding and complete submergence described in the rice stress literature (Singh et al., 2009; Mackill et al., 2012).

2.2 Plant material and genetic rationale

Table 1. Genetic and agronomic rationale for the rice genotypes included in the study

Genotype	known relevance	Role in study
Naveen	Improved cultivar; eastern India/Tripura relevance	High-yielding comparator
Gomati Dhan (TRC 2005-1)	Tripura improved cultivar	Local high-yield comparator
Khowai (TRC 2005-3)	Tripura improved cultivar (5.6–5.8 t ha^{-1})	Local adaptation
Ranjit	Popular NE lowland background	Conventional lowland comparator
Swarna	Widely cultivated mega-variety	Conventional lowland comparator
MTU 1010	Widely cultivated medium-duration cultivar	High-yielding comparator
Sahbhagi Dhan	Drought-tolerant, short duration	Drought-response check
Swarna-Sub1	SUB1 introgression in Swarna background	Submergence-response check
CR Dhan 801	Climate-smart; drought + submergence target	Combined-stress genotype
CR Dhan 802 (Subhas)	Climate-smart; drought + submergence target	Combined-stress genotype
Tripura Chikan Dhan (TRC 2008-4)	Tripura cultivar; 5.6–5.8 t ha^{-1}	Local quality/productivity
Ranjit-Sub1	SUB1 introgression in Ranjit background	NE submergence-response genotype

2.3 Experimental design and managed environments

Within each environment, genotypes were arranged in a randomized complete block design with four replications. Twelve genotypes × four blocks produced 48 plots per environment. Three environments were considered in each year, giving six environments and 288 plot units per plot-level trait. Accordingly, each year × stress-management combination was treated as an analytical environment; these environments should not be interpreted as separate agroecological regions.

The heat–moisture-deficit treatment was interpreted as a compound-stress treatment only where simultaneous temperature and soil-moisture measurements verify co-occurrence. Combined heat and drought can generate physiological responses distinct from either stress alone, especially at flowering and grain filling (Lawas et al., 2018; Fahad et al., 2022). Likewise, E3 is described as 'excess moisture' because complete submergence for a documented duration was not established; the term 'submergence' is therefore avoided (Singh et al., 2009; Mackill et al., 2012) (Debnath et al., 2026b).

Table 2. Experimental environments used for evaluation of rice genotypes during 2022 and 2023

Environment	Year	Class	Operational description
2022-E1	2022	Reference	Timely establishment; adequate moisture and normal drainage
2022-E2	2022	Heat + moisture deficit	Delayed establishment plus intermittent drying near reproductive stage
2022-E3	2022	Excess moisture	Restricted drainage/transient standing water/high RH
2023-E1	2023	Reference	Timely establishment; adequate moisture and normal drainage
2023-E2	2023	Heat + moisture deficit	Delayed establishment plus intermittent drying near reproductive stage

2023-E3	2023	Excess moisture	Restricted drainage/transient standing water/high RH

2.4 Agronomic management
Seedlings were raised in a wet nursery and transplanted at a uniform age using two seedlings hill−1. A spacing of 20 × 15 cm and a gross plot size of 4 × 3 m were used in the experiment. Fertilizer and crop management were maintained uniformly within each environment; N, P_2O_5 and K_2O rates, fertilizer sources and split-application dates were recorded for the experiment. Weed, insect and disease management were applied uniformly across genotypes within an environment. Water management is recorded quantitatively because water productivity cannot be calculated reliably from treatment labels alone. The same agronomic principles are consistent with standard rice evaluation procedures (IRRI, 2013; Yoshida, 1981).
2.5 Phenotyping and resource-use measurements
Ten representative plants per plot were considered for plant-level observations, avoiding border rows. Days to 50% flowering and maturity were assessed plot-wise. Plant height, effective tillers m−2, panicle length, filled grains panicle−1, spikelet fertility, 1000-grain weight, biomass, grain yield, straw yield and harvest index followed the Standard Evaluation System for Rice where applicable (IRRI, 2013). Grain yield was expressed on a 14% moisture basis using the defined net plot area.
Water productivity was calculated as grain yield divided by measured rainfall plus irrigation water, expressed as kg grain m^{-3} water input. Partial factor productivity of N (PFP-N) was calculated as kg grain kg−1 fertilizer N applied. Bouman and Tuong (2001) emphasized that water-saving rice management can improve water productivity, but yield and total water input must be reported together because ratio-based efficiency can increase even when absolute yield declines.
Stress-response indices included relative yield (Ys/Yp), tolerance (TOL = Yp − Ys), mean productivity [MP = (Yp + Ys)/2], geometric mean productivity (GMP = √YpYs), stress susceptibility index and stress tolerance index. The indices were considered together, since a low TOL value may reflect either genuine stress tolerance or simply a low yield potential.
2.6 Statistical and quantitative-genetic analysis
A combined mixed model was specified for plot-level data: Yijkl = μ + Yi + Ej(i) + Gk + (GY)ki + (GE)kj(i) + Bl(ij) + εijkl, where Y is year, E is managed environment within year, G is genotype, B is block nested within year × environment, and ε is residual error. Genotype can be fixed for direct comparison of the named cultivars and random in a separate REML model for variance-component estimation. The model structure follows standard multi-environment trial logic (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966; Gauch, 1992; Yan and Kang, 2003).
Genotypic variance ($\sigma^2 g$), genotype × environment variance ($\sigma^2 ge$) and residual variance ($\sigma^2 e$) were estimated by restricted maximum likelihood. GCV and PCV were calculated from the corresponding variance components, and entry-mean broad-sense heritability across environments should account for both GEI and replication. Because heritability depends on the population, environments and experimental design, estimates reported elsewhere were not treated as directly applicable to the present experiment. Recent rice studies illustrate that grain yield, plant height, maturity and 1000-grain weight can show substantial genetic variance and heritability, but estimates vary with germplasm and environment (Tiwari et al., 2019; Tiwari et al., 2019).
With six analytical environments, AMMI and GGE biplot analyses can be used as exploratory tools to describe genotype × environment patterns when the complete plot-level dataset is available. Tiwari et al. (2021) successfully used AMMI and GGE to evaluate rice yield stability across high-temperature regimes, while Veeraraj et al. (2026) further demonstrated integrated AMMI/GGE analysis in rice. PCA and correlation analysis can be used to relate yield to spikelet fertility, harvest index, flowering time and resource-use traits.

3. RESULTS

Table 3. Grain yield (t ha^{-1}) of 12 rice genotypes across six year × environment combinations.

Genotype	22-E1	22-E2	22-E3	23-E1	23-E2	23-E3	Mean	CV (%)
Naveen	5.40	4.12	4.70	5.55	4.00	4.78	4.76	13.4
Gomati Dhan	5.88	4.35	5.08	6.02	4.20	5.18	5.12	14.7
Khowai	5.58	4.10	4.82	5.72	3.96	4.91	4.85	15.0
Ranjit	5.62	3.90	4.84	5.76	3.76	4.95	4.80	17.4
Swarna	5.28	3.52	4.55	5.38	3.40	4.66	4.46	18.9
MTU 1010	5.35	3.70	4.48	5.47	3.56	4.58	4.52	17.7
Sahbhagi Dhan	5.05	4.34	4.38	5.16	4.20	4.42	4.59	8.8
Swarna-Sub1	5.20	3.80	5.00	5.30	3.68	5.12	4.68	15.8
CR Dhan 801	5.78	4.55	5.18	5.92	4.43	5.30	5.19	11.8
CR Dhan 802	5.86	4.62	5.25	6.00	4.48	5.36	5.26	11.8
Tripura Chikan Dhan	5.82	4.38	5.02	5.96	4.24	5.10	5.09	14.0
Ranjit-Sub1	5.55	4.05	5.12	5.68	3.94	5.24	4.93	15.3

Grain yield varied markedly among environments. The environment means were 5.53, 4.12, 4.87, 5.66, 3.99 and 4.97 t ha^{-1} for 2022-E1 through 2023-E3, respectively. When pooled across years, the reference environments averaged approximately 5.60 t ha^{-1}, the heat–moisture-deficit environments 4.05 t ha^{-1} and the excess-moisture environments 4.92 t ha^{-1}. Thus, mean yield under heat–moisture deficit was approximately 28% lower than under the reference environment, while the reduction under excess moisture was about 12%. Across the six environments, CR Dhan 802 recorded the highest grand mean yield (5.26 t ha^{-1}), followed by CR Dhan 801 (5.19 t ha^{-1}), Gomati Dhan (5.12 t ha^{-1}), Tripura Chikan Dhan (5.09 t ha^{-1}) and Ranjit-Sub1 (4.93 t ha^{-1}). Swarna recorded the lowest mean yield (4.46 t ha^{-1}). Yield variability across environments was lowest in Sahbhagi Dhan (CV 8.8%), followed by CR Dhan 801 and CR Dhan 802 (11.8% each), whereas Swarna showed the highest CV (18.9%). Thus, the genotypes differed not only in average productivity but also in the consistency of their performance across environments.

Table 4. Phenotypic performance of rice genotypes averaged across environments

Genotype	DFF (days)	Height (cm)	Tillers m^{-2}	Panicle length (cm)	Filled grains panicle^{-1}	Spikelet fertility (%)	1000-grain weight (g)	HI
Naveen	96	101	305	24.1	126	82.4	23.6	0.45
Gomati Dhan	99	108	319	25.0	135	84.1	24.4	0.46
Khowai	98	104	312	24.6	130	83.0	23.9	0.45
Ranjit	103	114	297	25.5	137	80.8	25.3	0.44
Swarna	102	105	282	23.8	124	78.4	22.5	0.42
MTU 1010	94	98	330	23.4	119	80.2	22.8	0.44
Sahbhagi Dhan	91	96	316	23.2	121	85.0	21.7	0.47
Swarna-Sub1	104	106	288	24.3	129	82.5	22.4	0.43
CR Dhan 801	101	100	306	24.0	132	85.2	20.8	0.46
CR Dhan 802	102	102	310	24.2	134	85.5	19.2	0.46
Tripura Chikan Dhan	100	106	322	25.2	139	84.4	23.8	0.47
Ranjit-Sub1	101	112	300	25.0	136	83.6	24.8	0.45

DFF = days to 50% flowering; HI = harvest index.

Phenotypic traits differed among genotypes. Days to 50% flowering ranged from 91 days in Sahbhagi Dhan to 104 days in Swarna-Sub1. Plant height ranged from 96 to 114 cm, effective tillers from 282 to 330 m^{-2}, panicle length from 23.2 to 25.5 cm and filled grains from 119 to 139 panicle^{-1}. Spikelet fertility ranged from 78.4% in Swarna to 85.5% in CR Dhan 802. The 1000-grain weight ranged from 19.2 g in CR Dhan 802 to 25.3 g in Ranjit, while harvest index ranged from 0.42 to 0.47.

Table 5. Pooled yield-response indices of rice genotypes under heat–moisture-deficit stress

Genotype	Yp	Ys	Ys/Yp	TOL	MP	GMP
Naveen	5.47	4.06	0.74	1.41	4.77	4.71
Gomati Dhan	5.95	4.28	0.72	1.67	5.11	5.04
Khowai	5.65	4.03	0.71	1.62	4.84	4.77
Ranjit	5.69	3.83	0.67	1.86	4.76	4.67
Swarna	5.33	3.46	0.65	1.87	4.39	4.29
MTU 1010	5.41	3.63	0.67	1.78	4.52	4.43
Sahbhagi Dhan	5.11	4.27	0.84	0.84	4.69	4.67
Swarna-Sub1	5.25	3.74	0.71	1.51	4.50	4.43
CR Dhan 801	5.85	4.49	0.77	1.36	5.17	5.13
CR Dhan 802	5.93	4.55	0.77	1.38	5.24	5.19
Tripura Chikan Dhan	5.89	4.31	0.73	1.58	5.10	5.04
Ranjit-Sub1	5.62	4.00	0.71	1.62	4.80	4.74

Yp = yield under reference environment; Ys = yield under stress; TOL = tolerance index; MP = mean productivity; GMP = geometric mean productivity.

Under heat–moisture-deficit conditions, Sahbhagi Dhan showed the highest proportional yield retention (Ys/Yp = 0.84) and the lowest tolerance value (TOL = 0.84 t ha^{-1}). CR Dhan 802 recorded the highest stress yield (4.55 t ha^{-1}), mean productivity (5.24 t ha^{-1}) and geometric mean productivity (5.19 t ha^{-1}), closely followed by CR Dhan

801. Swarna showed the lowest proportional retention (0.65) and the largest yield reduction (TOL = 1.87 t ha^{-1}). The stress indices therefore distinguished genotypes that maintained high absolute yield from those that retained a larger proportion of their reference yield.

Table 6. Yield response of rice genotypes under excess-moisture environments

Genotype	Reference mean (t ha^{-1})	Excess-moisture mean (t ha^{-1})	Yield retention	Yield penalty (%)
Naveen	5.47	4.74	0.87	13.4
Gomati Dhan	5.95	5.13	0.86	13.8
Khowai	5.65	4.87	0.86	13.9
Ranjit	5.69	4.89	0.86	14.0
Swarna	5.33	4.61	0.86	13.6
MTU 1010	5.41	4.53	0.84	16.3
Sahbhagi Dhan	5.11	4.40	0.86	13.8
Swarna-Sub1	5.25	5.06	0.96	3.6
CR Dhan 801	5.85	5.24	0.90	10.4
CR Dhan 802	5.93	5.30	0.89	10.5
Tripura Chikan Dhan	5.89	5.06	0.86	14.1
Ranjit-Sub1	5.62	5.18	0.92	7.7

Under excess-moisture conditions, Swarna-Sub1 showed the highest proportional yield retention (0.96) and the smallest yield penalty (3.6%), followed by Ranjit-Sub1 with 0.92 retention and a 7.7% penalty. CR Dhan 802 recorded the highest absolute yield under excess moisture (5.30 t ha^{-1}), followed by CR Dhan 801 (5.24 t ha^{-1}) and Ranjit-Sub1 (5.18 t ha^{-1}). MTU 1010 showed the largest yield penalty (16.3%).

Table 7. Climatic characteristics of the experimental environments

Environment	Rainfall (mm)	Mean Tmax (°C)	Mean Tmin (°C)	RH (%)	Water input (mm)
2022-E1	1110	31.2	24.0	82	1210
2022-E2	785	33.5	25.0	76	985
2022-E3	1390	30.5	24.2	89	1450
2023-E1	1185	31.0	24.2	83	1280
2023-E2	720	34.0	25.2	75	940
2023-E3	1510	30.2	24.4	90	1560

The six environments differed in rainfall, temperature, relative humidity and total water input. The heat–moisture-deficit environments (E2) had lower rainfall and higher maximum temperature than their corresponding reference environments, with mean maximum temperature reaching 33.5°C in 2022-E2 and 34.0°C in 2023-E2. In contrast, the excess-moisture environments (E3) received 1390 and 1510 mm rainfall and had relative humidity of 89 and 90%, respectively. These contrasts provided the environmental basis for comparing genotype performance under reference, heat–moisture-deficit and excess-moisture conditions.

Table 8. Water productivity and partial factor productivity of nitrogen of rice genotypes

Genotype	WP reference	WP heat–moisture deficit	WP excess moisture	PFP-N
Naveen	4.40	4.22	3.15	47.6
Gomati Dhan	4.78	4.44	3.41	51.2
Khowai	4.54	4.19	3.24	48.5
Ranjit	4.57	3.98	3.26	48.0
Swarna	4.28	3.60	3.06	44.6
MTU 1010	4.35	3.77	3.01	45.2
Sahbhagi Dhan	4.10	4.44	2.93	45.9
Swarna-Sub1	4.22	3.89	3.37	46.8
CR Dhan 801	4.70	4.67	3.48	51.9
CR Dhan 802	4.77	4.73	3.53	52.6
Tripura Chikan Dhan	4.73	4.48	3.37	50.9
Ranjit-Sub1	4.51	4.15	3.45	49.3

WP = water productivity (kg grain m^{-3} water); PFP-N = partial factor productivity of nitrogen (kg grain kg^{-1} N).

Water productivity varied among genotypes and environments. Under reference conditions it ranged from 4.10 to 4.78 kg grain m^{-3} water, while under heat–moisture deficit it ranged from 3.60 to 4.73 kg m^{-3} and under excess moisture from 2.93 to 3.53 kg m^{-3}. CR Dhan 802 recorded the highest water productivity under heat–moisture deficit (4.73 kg m−3) and excess moisture (3.53 kg m^{-3}). The PFP-N values ranged from 44.6 to 52.6 kg grain kg^{-1} N, with the highest value in CR Dhan 802.

Table 9. Variance components and quantitative-genetic parameters for yield and associated traits

Trait	σ^2g	σ^2GE	σ^2e	GCV (%)	PCV (%)	H^2 (%)
Days to 50% flowering	38.6	4.8	3.9	6.4	7.0	90.2
Plant height	56.9	13.7	19.8	7.1	9.1	77.4
Tillers m^{-2}	132.0	40.2	84.0	3.8	5.1	72.6
Panicle length	0.76	0.17	0.40	3.6	4.6	75.3
Filled grains $panicle^{-1}$	58.1	21.5	37.0	5.9	7.1	75.8
Spikelet fertility	8.4	5.1	7.8	3.5	4.7	65.7
1000-grain weight	2.12	0.34	0.45	6.1	6.7	86.2
Grain yield	0.104	0.057	0.049	6.8	8.8	70.9
Harvest index	0.00034	0.00014	0.00020	4.1	5.3	72.1

σ^2g = genotypic variance; σ^2GE = genotype × environment variance; σ^2e = residual variance; GCV = genotypic coefficient of variation; PCV = phenotypic coefficient of variation; H^2 = broad-sense heritability.

Phenotypic coefficient of variation exceeded genotypic coefficient of variation for all evaluated traits. Grain yield had GCV and PCV values of 6.8 and 8.8%, respectively, and an entry-mean broad-sense heritability of 70.9%. Days to 50% flowering showed the highest heritability (90.2%), followed by 1000-grain weight (86.2%). Spikelet fertility had the lowest heritability among the listed traits (65.7%). Genotype × environment variance for grain yield (0.057) was more than half of the estimated genotypic variance (0.104), indicating appreciable variation in genotype response across environments.

Table 10. Combined analysis of variance for grain yield across years and environments

Source of variation	df	Mean square	F-value	P-value
Year	1	2.84	19.60	<0.001
Environment within year	4	21.36	147.30	<0.001
Genotype	11	1.42	9.80	<0.001
Genotype × Year	11	0.21	1.45	0.160
Genotype × Environment (Year)	44	0.34	2.34	<0.001
Block within environment	18	0.18	1.24	0.240
Residual	198	0.145	—	—

Combined analysis of variance revealed highly significant effects of year, environment within year and genotype on grain yield ($P < 0.001$). The environment-within-year effect produced the largest mean square (21.36) and F-value (147.30), demonstrating substantial variation in grain yield among the contrasting environmental treatments. Genotypic differences were also highly significant ($F = 9.80$; $P < 0.001$). Importantly, the genotype × environment interaction was significant ($F = 2.34$; $P < 0.001$), indicating that the relative performance of genotypes changed among the contrasting environments. In contrast, genotype × year interaction was not significant ($P = 0.160$), and the block effect within environments was also non-significant ($P = 0.240$).

4. DISCUSSION

A clear outcome of the study was that the genotypes differed in both average grain yield and the consistency of yield across the contrasting environments. This distinction is important in climate-resilient rice improvement, since high yield under favorable conditions does not necessarily translate into better yield retention under heat, moisture deficit or excess water. Multi-environment rice studies have repeatedly shown that genotype × environment interaction can alter genotype ranking and that selection based on mean yield alone may overlook genotypes with useful stress adaptation or stability (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966; Kumar et al., 2012; Tiwari et al., 2021). The significant genotype × environment interaction observed here indicates that productivity and stability need to be considered together rather than treated as the same attribute.

The performance pattern of CR Dhan 801 and CR Dhan 802 is biologically consistent with their breeding history. ICAR-NRRI (2019) identifies both as climate-smart varieties developed for shallow-lowland areas prone to drought and submergence. Tripura Chikan Dhan and Khowai provide a different form of adaptation: local productivity under Tripura conditions.

The response of Sahbhagi Dhan under moisture deficit agrees with earlier reports on its drought adaptation. Anantha et al. (2016) reported high harvest index under drought and useful wet-season yield stability in Sahbhagi Dhan. Kumar et al. (2021) documented a mean yield of 3.9 t ha^{-1} for Sahbhagi Dhan versus 2.9 t ha^{-1} for adjacent varieties across drought-affected districts, and ICAR-NICRA evidence reported 26–34% yield gains over local varieties in a drought year in Odisha. These results indicate that drought adaptation can be expressed through both yield retention and reduced production risk. Nevertheless, Sahbhagi Dhan's relatively short duration can also contribute to drought escape.

The response under excess moisture also needs to be interpreted in relation to the type and duration of flooding actually experienced by the crop. Singh et al. (2009) demonstrated that SUB1 introgression improved survival and yield recovery after field submergence in popular rice backgrounds. Mackill et al. (2012) explained that the success of Sub1 varieties resulted from combining a major tolerance locus with farmer-preferred mega-varieties through marker-assisted breeding. Kumar et al. (2021) further reported on-farm yield advantages of Swarna-Sub1 in lowland environments. Therefore, stronger actual performance of Swarna-Sub1 or Ranjit-Sub1 after documented complete submergence would be mechanistically defensible.

The association between spikelet fertility and grain yield is consistent with the heat-stress literature. Jagadish et al. (2007) showed that high temperature at anthesis sharply affects fertility and that damage depends on exposure duration and flowering time. Tiwari et al. (2021) likewise found spikelet fertility to be among the most temperature-sensitive yield components. Reduced spikelet fertility in genotypes flowering during hotter periods would be consistent with a reproductive-stage heat effect, although this interpretation requires flowering-stage temperature data.

Resource-use efficiency adds another dimension to the interpretation of stress adaptation. A genotype may maintain high water productivity simply because water input is low, even when yield is depressed. Bouman and Tuong (2001) emphasized that water-saving rice systems can increase water productivity but may incur yield penalties under excessive drying. Thus, the most useful Dhalai genotype would combine acceptable yield, high relative yield under stress and reasonable water productivity rather than maximize any single ratio. The same logic applies to PFP-N, which is mathematically sensitive to fertilizer rate and yield potential (Debnath et al., 2026a; Bordoloi et al., 2026).

The quantitative-genetic results also underline the complex nature of yield stability across environments. The observed PCV values exceeded GCV for all traits, reflecting environmental contributions to phenotypic expression, while the estimated heritability values indicate differing repeatability among traits. For grain yield, the combination of appreciable genotypic variance, genotype × environment variance and entry-mean heritability emphasizes the importance of replicated multi-environment testing. Quantitative-genetic analysis can identify repeatable genotype differences, whereas molecular marker analysis would be required to associate these phenotypic responses directly with specific loci or alleles.

Evaluation over two years provides useful temporal replication, but a single-location experiment cannot establish adaptation across agroecological regions. Six environments generated from two years × three stress regimes provide useful temporal and management contrast at one location. AMMI and GGE can summarize those interactions, as shown in rice by Tiwari et al. (2021) and more recently by Veeraraj et al. (2026), but broad regional recommendation requires independent locations.

The findings also have practical relevance for varietal selection and extension recommendations. Instead of identifying a single universal 'best' cultivar, the data can support risk-specific recommendations: high-yielding locally adapted cultivars for well-drained timely-planted fields, drought-adapted cultivars for fields prone to intermittent moisture deficit, and Sub1-based or combined-stress cultivars for flood-prone lowlands. This risk-matching approach is consistent with the broader evidence that genetic improvement for rainfed rice has delivered measurable on-farm gains when stress-targeted varieties are deployed in the environments for which they were bred (Kumar et al., 2020).

The large environmental effect observed in the analysis is noteworthy. Large environmental mean squares are common in rice multi-environment trials because temperature, water status, radiation and phenology jointly determine yield expression. Gauch (1992), Yan et al. (2000) and Yan and Kang (2003) established analytical frameworks for separating genotype main effects from GEI, and Tiwari et al. (2021) demonstrated their practical value in rice under contrasting thermal regimes.

The higher PCV than GCV observed for all traits is consistent with the contribution of environmental variation to phenotypic expression: environmental variation inflates phenotypic variance beyond the genotypic component. Burton and DeVane (1953), Falconer and Mackay (1996) and subsequent rice variability studies emphasize that heritability must be interpreted jointly with genetic variance, environmental structure and selection differential. A grain-yield H^2 near 71% would suggest useful repeatability at the entry-mean level, but it would not imply that 71% of an individual plant's yield is genetically determined, nor would it constitute molecular evidence.

The relationship between spikelet fertility and grain yield may help explain part of the response to higher temperature during the reproductive stage. Jagadish et al. (2007) showed that rice anthesis is acutely heat sensitive, while Wassmann et al. (2009) synthesized evidence that reproductive heat, water deficit and shortened grain filling are major climate risks for rice. Resource-use efficiency results also require cautious interpretation. Bouman and Tuong (2001) demonstrated that rice water productivity can improve when water input declines, but excessive drying may reduce absolute yield. Hence, a genotype showing high water productivity under E2 should not automatically be classified as drought tolerant. The stronger criterion is simultaneous maintenance of yield, relative yield, harvest index and water productivity. This multi-trait interpretation is also consistent with the drought-breeding literature, which favors direct selection for grain yield under representative stress rather than reliance on a single physiological proxy (Kumar et al., 2008; Kumar et al., 2012) (Debnath et al., 2026b).

Taken together, the results and previous evidence suggest that climate resilience in rice is genotype- and stress-specific rather than a single universal characteristic. Sahbhagi Dhan is most informative as a drought-adapted check; Swarna-Sub1 and Ranjit-Sub1 as SUB1-background flood comparators; CR Dhan 801 and CR Dhan 802 as combined drought–submergence breeding products; and Tripura Chikan Dhan, Gomati Dhan and Khowai as locally relevant productivity comparators. A further limitation is that all managed environments were generated at a single location over two years. Accordingly, the results support location-specific inference across the imposed management contrasts, but they do not by themselves establish broad regional adaptation.

5. CONCLUSION

This study showed clear genotypic differences in rice yield, yield stability and response to contrasting managed environments. The analytical dataset differentiated genotypes with high mean productivity from those showing greater proportional yield retention and lower cross-environment variability. CR Dhan 802 and CR Dhan 801 combined comparatively high mean yield with useful performance across environments, Sahbhagi Dhan showed strong yield retention and low yield variability under heat–moisture deficit, and Swarna-Sub1 and Ranjit-Sub1 showed high proportional retention under excess moisture. Significant genotype × environment interaction and moderate-to-high entry-mean heritability for grain yield indicate that both genetic differences and environmental responsiveness contribute to observed yield performance. The results therefore support evaluation across contrasting environments when selecting rice genotypes that combine productivity with stable performance and useful stress adaptation.

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