



## GENETIC VARIATION, COMBINING ABILITY, AND SEEDLING-STAGE DROUGHT TOLERANCE IN RICE (*ORYZA SATIVA* L.) HYBRIDS

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**ABSTRACT:** Seedling-stage drought stress significantly constrains rice production in Nigeria's rainfed ecosystems. This study evaluated genetic variation, combining ability, gene action, and performance of rice topcross hybrids for drought tolerance at the seedling stage. Using a line × tester mating design, 125 F<sub>1</sub> hybrids were generated from five cytoplasmic male-sterile (CMS) lines and 25 testers, then screened under greenhouse moisture stress using morphological traits, survival, recovery parameters, and drought-tolerance indices in a Completely Randomized Design with three replications. Drought effects were more pronounced in recovery traits than early injury symptoms, indicating stronger genetic differentiation during post-stress regrowth. Significant line × tester interactions for drought recovery score, survival rate, and plant height confirmed predominant non-additive gene action governing seedling resilience. Genetic parameters showed moderate additive variance and heritability for leaf rolling, leaf drying, and plant height ( $h^2 = 0.18-0.24$ ), while drought injury, survival, and recovery traits were largely influenced by environmental and non-additive effects. Correlation analyses revealed stress tolerance index (STI) showed near-perfect negative association with stress susceptibility index (SSI). Superior hybrids identified included IR75596A × IRRI 186, IR79125A × IR112899-11-2-1, and IR93559A × IR60912-93-3-2-3-3R, combining low injury, high survival, and strong recovery. Female line IR75596A contributed drought avoidance through reduced leaf symptoms, IR93559A enhanced recovery ability, while tester IRRI 186 showed outstanding combining ability for recovery traits.

**Keywords:** Combining ability, Drought recovery, Hybrid rice, Line × tester, Seedling-stage stress

### INTRODUCTION

Rice (*Oryza sativa* L.) is a cornerstone to food security and livelihoods in Nigeria, with consumption rising rapidly due to population growth and

urbanization (FAO, 2022). Despite progress in expanding cultivation, domestic production remains unstable, largely due to recurrent drought, a major abiotic stress exacerbated by climate change among many other factors (Akinseye *et al.*, 2020). Over 70% of Nigeria's rice is grown in rainfed lowland and upland systems, which are acutely vulnerable to rainfall variability (Saito *et al.*, 2015) Climate

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projections indicate an increased frequency of early-season dry spells in the Sudano-Sahelian and Guinea savanna zones, where delayed or erratic rains critically impair seedling establishment, reduce tillering, and can necessitate costly replanting, leading to substantial yield losses (Oladosu *et al.*, 2021; Ayanlade *et al.*, 2023). Consequently, enhancing seedling-stage drought tolerance is a strategic priority for stabilizing rice production in Nigeria's rainfed ecologies.

Breeding for drought tolerance in rice requires a clear understanding of its genetic architecture. Drought resilience is a complex trait involving distinct physiological mechanisms such as dehydration avoidance, tissue tolerance, and post-stress recovery capacity (Coulter *et al.*, 2022; Basu *et al.*, 2022). In rainfed systems, where intermittent moisture stress is common, the ability to recover after rewatering is critical and may be genetically independent from avoidance traits (Sandhu *et al.*, 2021). Genetic variance for such complex traits comprises both additive effects, which are heritable and selectable in inbred lines, and non-additive (dominance and epistatic) effects, which are crucial for hybrid performance (Kumar *et al.*, 2022). The line  $\times$  tester mating design is an established method to partition these effects, estimate general combining ability (GCA, additive) and specific combining ability (SCA, non-additive), and identify superior parental combinations for hybrid breeding (Yan and Wang, 2022).

In Nigeria, hybrid rice is increasingly recognized for its yield advantage and stability under stress, studies have identified some promising hybrid candidate for improving rice productivity in Nigeria (Igyuve *et al.*, 2025c). However, there is scarcity of studies that integrate combining ability analysis with detailed phenotyping for seedling-stage drought tolerance using germplasm relevant to local breeding programs in rice. This study utilized genetically diverse cytoplasmic male sterile (CMS) and restorer lines sourced from the Hybrid Rice Development Consortium (HRDC), International Rice Research Institute (IRRI) to address this gap. The objectives of this study were to; evaluate genetic variation and combining ability in rice topcross hybrids under seedling-stage drought stress; estimate heritability and genetic advance for key drought-responsive traits; analyze trait interrelationships using multivariate methods; and identify superior hybrids and parental

lines for breeding drought-resilient rice varieties for Nigeria's rainfed ecosystems.

## MATERIALS AND METHODS

### Plant Materials and Experimental Design

A total of 125 rice hybrids were developed using a line  $\times$  tester mating design involving five cytoplasmic male-sterile maintainer (B) lines and 25 male testers (19 restorer lines and six converted commercial varieties; Table 1), similarly, Physicochemical properties of the soil prior to drought seedling trial was analyzed (Table 2). The hybrids and their parents were evaluated for seedling-stage drought tolerance under controlled greenhouse conditions at the Rice Research Station, Value Village, Zaria Kaduna State Nigeria (Lat. 11.2197985° and long. 7.7780668°) northern Guinea savannah ecological zone of Nigeria.

### Seedling-Stage Drought Screening

Drought screening was conducted using a PVC-Mylar tube system adapted from IRRI (2021). Soil-filled Mylar tubes (40 cm depth) were inserted into sealed PVC cylinders, allowing precise control of soil moisture and complete recovery of root systems at harvest. Soil field capacity was determined gravimetrically. Seeds were pre-germinated at 30 °C for 48 hrs and sown at approximately 75% field capacity to initiate a controlled dry-down process.

The experiment was arranged in a Completely Randomize Design (CRD) with three replications, one plant per tube and two tubes per plot. Fertilizer was applied at 120 kg N, 60 kg P<sub>2</sub>O<sub>5</sub>, and 60 kg K<sub>2</sub>O ha<sup>-1</sup>, calculated relative to soil weight per tube (IRRI, 2021). Seedlings were irrigated until 14 days after planting, after which water was withheld from drought treatments for 28 days, while control plants were continuously irrigated.

### Trait Measurement

Drought response was assessed using modified Standard Evaluation System (SES) scores for leaf rolling, leaf drying, and visual drought injury at the seedling and vegetative stages (IRRI, 2021; Lang *et al.*, 2012). Growth and root traits measured included plant height, maximum root length, root number, root volume, root diameter, shoot dry weight, root dry weight, and root-to-shoot ratio. Biomass samples were oven-dried at 70 °C for 48 hrs before weighing.

**Table 1.** Plant Materials Evaluated for Drought Stress Tolerance.

S/N	Designation	Type	Origin	Ecotype
1	IR75596A/B	Maintainer Line	IRRI	Indica
2	IR78369A/B	Maintainer Line	IRRI	Indica
3	IR79125A/B	Maintainer Line	IRRI	Indica
4	IR93559A/B	Maintainer Line	IRRI	Indica
5	IR93560A/B	Maintainer Line	IRRI	Indica
6	C4842-2-3-2-1-1R	R-Line	IRRI	Indica
7	IR 60912-93-3-2-3-3 R	R-Line	IRRI	Indica
8	IR 85593-23-2-1-3-1-3-1-1-1	R-Line	IRRI	Indica
9	IR85538-2-1-1-1-1-1-1-1R	R-Line	IRRI	Indica
10	IR86515-19-1-2-1-1-1-1R	R-Line	IRRI	Indica
11	IR86526-10-4-1-1-1-1	R-Line	IRRI	Indica
12	IR86612-13-1-1-1-1R	R-Line	IRRI	Indica
13	IRRI 143	R-Line	IRRI	Indica
14	IRRI 179	R-Line	IRRI	Indica
15	IRRI 184	R-Line	IRRI	Indica
16	IRRI 186	R-Line	IRRI	Indica
17	IR112867-28-1-1	R-Line	IRRI	Indica
18	IR112898-35-1-1	R-Line	IRRI	Indica
19	IR112899-11-2-1	R-Line	IRRI	Indica
20	IR101999-25-2-2	R-Line	IRRI	Indica
21	IR98145-3-2-1-1-2-1-1	R-Line	IRRI	Indica
22	IR98153-15-1-1-1-1-1-1	R-Line	IRRI	Indica
23	IR98155-75-1-1-1-1-1-1	R-Line	IRRI	Indica
24	IR98220-3-2-1-1-2-1-1	R-Line	IRRI	Indica
25	Faro 67	Commercial variety	NCRI	Indica
26	Local Variety	Commercial variety		Indica
27	UPIA 2	Commercial variety	Uniport	Indica
28	UPIA 3	Commercial variety	Uniport	Indica
29	Faro 59	Commercial variety	NCRI	Indica
30	Faro 58	Commercial variety	NCRI	Indica

**Table 2.** Soil Physicochemical Conditions at the Experimental Site Pre-Drought Treatment

(Mg/kg)	pH	%			µS/cm	Cmol/kg						%			Textural Class	
		H <sub>2</sub> O	OC	OM		N	E.C	Na	K	Ca	Mg	H + Al	40 sec.	2 hrs.		Clay
33.81	7.22	0.39	0.67	0.04	0.07	0.16	0.23	4.00	1.20	0.40	21	3	10	36	54	SL
11.27	7.12	0.34	0.58	0.06	0.07	0.10	0.18	2.20	0.66	0.40	22	3	10	38	52	SL
11.27	7.01	0.32	0.55	0.06	0.05	0.11	0.21	4.00	1.20	0.40	21	3	10	36	54	SL

### Statistical Analysis

All collected data were subjected to analysis of variance (ANOVA) using SAS software version 9.4 (SAS Institute, 2011). Mean separation was performed using Fisher's least significant difference (LSD) test at a 5% probability level. The following random-effects model was applied:

$$Y_{ijk} = \mu + G_i + \beta_j + \gamma_{k(j)} + \varepsilon_{ijk} \quad (\text{González-Barríos et al., 2019})$$

Where,  $Y_{ijk}$ ,  $\mu$ ,  $G_i$ ,  $\beta_j$ ,  $\gamma_{k(j)}$  and  $\varepsilon_{ijk}$  are observation of the  $i^{\text{th}}$  genotype and  $j^{\text{th}}$  replication, overall mean, effect of the  $i^{\text{th}}$  genotype, effect the  $j^{\text{th}}$  replication, and random error, respectively. Genotypes = random, Replications = random

## RESULTS AND DISCUSSION

### Genotypic Response Patterns and Interaction Effects under Seedling-Stage Drought Stress

The mean square analysis of variance (Table 3) revealed that drought treatment effects were significant only for plant height at recovery (PHT\_REC), indicating that recovery traits were more responsive to stress than immediate injury symptoms. This finding corroborates reports by Sandhu *et al.* (2022), who observed stronger genotypic differentiation in seedling recovery traits compared to early injury scores. Non-significant differences among parental lines align with Challam *et al.* (2021), who noted narrow phenotypic variation among inbred lines at the seedling stage. However, a significant parent-cross contrast was observed for drought injury score at 7 days after imposing stress (DIS\_7DAIS), supporting Mwando *et al.* (2020), who reported enhanced stress responses in hybrids due to heterotic interactions.

The absence of significant variation among crosses, lines, and testers for most traits contrasts with Dixit *et al.* (2023), suggesting that environmental variability or insufficient stress intensity may have minimized detectable differences during the stress phase. In contrast, significant Line  $\times$  Tester interactions were observed for drought recovery score (DRS), survival rate (SR %), and plant height at 28 days after stress (PHT\_28DAIS) and at recovery (PHT\_REC). These results agree with Sandhu *et al.* (2022) and Mwando *et al.* (2020), confirming that recovery and survival traits are governed predominantly by non-additive gene action. This emphasizes the importance of specific parental combinations in achieving superior post-stress regrowth in hybrids.

### Estimating Gene Action and Heritability for Seedling-Stage Drought Response

The estimation of genetic parameters (Table 4) revealed measurable additive genetic variance and low to moderate narrow-sense heritability for leaf rolling and leaf drying traits ( $\sigma^2_A = 0.16\text{--}0.18$ ;  $h^2 = 0.06\text{--}0.18$ ). This indicates that these drought-avoidance mechanisms possess a heritable component but remain strongly influenced by environmental effects. These results are consistent with Kumar *et al.* (2023), who reported that easily scored morphological stress indicators in rice seedlings often exhibit quantifiable genetic variance but are highly susceptible to micro-environmental fluctuations during screening. The wide divergence between genotypic (GCV) and phenotypic (PCV) coefficients

of variation further supports the high environmental variance component typical of pot-based seedling drought trials, as emphasized by Henry *et al.* (2022).

Higher additive variance and relatively greater heritability were observed for early and mid-stress plant height ( $\sigma^2_A = 1.98\text{--}2.54$ ;  $h^2 = 0.20\text{--}0.24$ ), supporting its use as a stable selection criterion. This agrees with Panda *et al.* (2022), who reported that seedling shoot growth parameters under stress generally show higher and more stable heritability estimates compared to physiological stress scores in rice breeding populations.

In contrast, several key integrative traits including drought injury scores at 7 and 21 days, drought recovery score, survival rate, cumulative water loss, and dry biomass weight recorded zero additive and dominance variance, resulting in zero heritability ( $H^2 = h^2 = 0.00$ ) and zero genetic advance. This observation aligns with Grondin *et al.* (2023), who found that seedling survival and similar resilience traits often exhibit low heritability unless assessed with highly standardized, high-throughput phenotyping platforms that minimize error. The complex variance structure for root length at recovery, which showed very low heritable expression, reflects the challenges reported by Shi *et al.* (2021), who concluded that root trait heritability in rice is frequently low in early-generation material due to polygenic control and high genotype-by-environment interaction.

### Correlation Structure of Drought Tolerance Indices

The correlation analysis (Figure 1) revealed a near-perfect negative association between the Stress Tolerance Index (STI) and the Stress Susceptibility Index (SSI) ( $r = -1.00$ ). This strong inverse relationship aligns with the classical expectation that genotypes with higher tolerance express lower susceptibility under drought, as validated by Ahmad *et al.* (2022) in screening for terminal drought tolerance in rice. The nearly perfect positive correlation between Tolerance Index (TOL) and Mean Productivity (MP) ( $r = 0.99$ ) agrees with modern interpretations that both indices strongly favor high-yielding potential, as reported by Lafarge *et al.* (2020) in their analysis of yield-based drought indices in cereals.

**Table 3.** Mean squares from line × tester analysis of rice topcrosses under drought stress condition

SOV	DF	DIS_7DAIS	DIS_21DAIS	DIS_28DAIS	DRS	SR (%)	LR_28DAIS	LD_28DAIS	PHT_7DAP	PHT_28DAIS	PHT_REC	DBW	RL_REC
Replication	2	168.28	732.35	1727.33	7.39	1.19	1694.95	1708.49	168.78	0.37	241.47	250.71	6864.66
Treatment	1	0.16	0.01	0.09	0.05	0.02	0.16	0.00	0.54	1.25	43.73*	0.27	0.72
Parents	29	0.63	0.57	0.63	0.31	0.15	0.68	0.96	8.67	8.11	0.67	0.27	24.20
Parents vs cross	1	9.44*	9.02	9.46	0.62	0.49	5.29	2.53	10.20	5.81	1.54	1.46	96.95
Cross	124	0.62	0.62	0.67	0.26	0.09	0.55	0.72	9.18	7.05	0.47	0.39	12.19
Lines	4	1.16	1.04	1.61	0.12	0.02	0.92	0.37	3.20	3.24	0.17	0.08	4.99
Tester	24	0.64	0.61	0.72	0.29	0.06	0.62	0.44	9.13	4.23	0.53	0.28	10.87
Line x tester	96	0.59	0.60	0.62	0.26*	0.09*	0.52	0.81	9.44	7.91*	0.47*	0.43	12.82
Error	183	2.91	9.06	19.91	1.73	0.59	19.49	19.97	18.37	40.24	3.56	3.37	106.22

**DIS\_7DAIS:** Drought injury score 7 days after imposing stress, **DIS\_21DAIS:** Drought injury score 21 days after imposing stress, **DIS\_28DAIS:** Drought injury score 28 days after imposing stress, **DRS:** Drought recovery score, **SR%:** Survival Rate percentage, **LR\_28DAIS:** Leaf rolling 28 days after imposing stress, **LD\_28DAIS:** Leaf drying 28 days after imposing stress, **PHT\_7DAP:** Plant height (cm) 7 days after planting, **PHT\_28DAIS:** Plant height (cm) 28 days after imposing stress, **PHT\_REC:** Plant height at recovery, **DBW:** Dry biomass weight (g), **RL\_REC:** Root length (cm) at recovery

**Table 4.** Estimates of genetic parameters rice topcross under drought stress at seedling stage

Trait	Mean	$\sigma^2A$	$\sigma^2D$	$\sigma^2G$	$\sigma^2E$	$\sigma^2P$	GCV (%)	PCV (%)	GCA:SCA	$h^2$	$H^2$	GA	GA (%)
DIS_7DAIS	0.12	0.00	0.00	0.00	0.97	0.97	0.00	816.67	NE	0.00	0.00	0.00	0.00
DIS_21DAIS	0.12	0.00	0.00	0.00	0.96	0.96	0.00	816.67	NE	0.00	0.00	0.00	0.00
DIS_28DAIS	0.12	0.00	0.20	0.20	0.90	1.10	0.00	875.00	<1.0	0.00	0.18	0.00	0.00
DRS	0.07	0.00	0.00	0.00	0.33	0.33	0.00	821.43	NE	0.00	0.00	0.00	0.00
SR (%)	0.04	0.00	0.00	0.00	0.10	0.10	0.00	791.67	NE	0.00	0.00	0.00	0.00
LR_7DAIS	0.05	0.00	0.00	0.00	0.18	0.18	0.00	848.53	NE	0.00	0.00	0.00	0.00
LR_21DAIS	0.12	0.16	0.00	0.16	0.85	1.01	333.33	838.89	>1.0	0.16	0.16	0.66	550
LR_28DAIS	0.11	0.18	0.00	0.18	0.83	1.01	385.97	914.55	>1.0	0.18	0.18	0.76	691
LD_7DAIS	0.13	0.00	0.04	0.04	0.17	0.21	0.00	353.85	<1.0	0.00	0.19	0.00	0.00
LD_21DAIS	0.13	0.08	0.00	0.08	1.16	1.24	217.39	856.41	>1.0	0.06	0.06	0.38	292
LD_28DAIS	0.13	0.10	0.00	0.10	1.14	1.24	243.08	856.41	>1.0	0.08	0.08	0.45	346
CWL_D7	0.00	0.00	0.00	0.00	0.00	0.00	NE	NE	NE	NE	NE	0.00	0.00
CWL_D14	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	NE	NE	NE	0.00	0.00
CWL_D21	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	NE	NE	NE	0.00	0.00
CWL_D28	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	NE	NE	NE	0.00	0.00
PHT_7DAP	0.36	2.54	0.00	2.54	8.07	10.61	442.59	905.56	>1.0	0.24	0.24	2.82	783
PHT_28DAIS	0.35	1.98	0.00	1.98	7.97	9.95	401.9	900.00	>1.0	0.20	0.20	2.28	651
PHT_REC	0.13	0.02	0.00	0.02	1.08	1.10	108.70	807.69	>1.0	0.02	0.02	0.10	77.00
DBW	0.01	0.00	0.00	0.00	0.01	0.01	0.00	100.00	NE	0.00	0.00	0.00	0.00
RL_REC	0.47	0.06	0.04	0.10	14.00	14.10	52.13	798.94	≈1.0	0.004	0.007	0.12	26.00
NL	0.12	0.04	0.00	0.04	0.87	0.91	166.67	791.67	>1.0	0.04	0.04	0.16	133.00
RR	0.03	0.00	0.00	0.00	0.05	0.05	0.00	745.36	NE	0.00	0.00	0.00	0.00

**Footnote:** Extremely high PCV values resulted from near-zero trait means and should be interpreted with caution. Zero or non-estimable variance and heritability estimates reflect limited genetic expression under severe drought stress and high experimental error, which are common in seedling-stage drought screening under controlled conditions.

**Key:**  $\sigma^2A$ : Additive genetic variance,  $\sigma^2D$ : Dominance genetic variance,  $\sigma^2G$ : Genotypic variance,  $\sigma^2E$ : Environmental variance,  $\sigma^2P$ : Phenotypic variance, GCV (%): Genotypic coefficient of variation, PCV (%): Phenotypic coefficient of variation, ECV (%): Environmental coefficient of variation, GCA:SCA: Ratio of general combining ability to specific combining ability,  $h^2$ : Narrow-sense heritability,  $H^2$ : Broad-sense heritability, GA: Genetic advance, GA (%): Genetic advance as a percentage of the mean, NE: Non-estimable, DIS (7DAIS, 21DAIS, 28DAIS): Drought injury score 7, 21 & 28 days after imposing stress, DRS: Drought recovery score, SR%: Survival Rate percentage, LR (7DAIS, 28DAIS): Leaf rolling 7 & 28 days after imposing stress, LD (7DAIS, 28DAIS): Leaf drying 7 & 28 days after imposing stress, CWL (D7, D14, D21, D28): Cumulative water loss at 7, 14, 21 & 28 days, PHT\_7DAP: Plant height (cm) 7 days after planting, PHT\_28DAIS: Plant height 28 days after imposing stress (cm), PHT\_REC: Plant height at recovery, DBW: Dry biomass weight (g), RL\_REC: Root length (cm) at recovery, NL: Number of leaves, RR: Recovery Rate

**Table 5A.** Estimation of the General Combining Ability (GCA) Effects of lines evaluated for drought stress at seedling stage

Lines	DIS_7DAIS	DIS_21DAIS	DIS_28DAIS	DRS	SR (%)	LR_7DAIS	LR_21DAIS	LR_28DAIS	LD_7DAIS	LD_21DAIS	LD_28DAIS
IR75596A	-0.08	-0.15	-0.10	0.03	0.05	-0.08	-0.33*	-0.37*	-0.07	-0.36*	-0.39*
IR78369A	-0.01	-0.03	-0.09	-0.08	-0.07*	0.00	-0.11	-0.12	-0.01	0.18	0.17
IR79125A	0.15	0.14	0.12	-0.01	-0.02	0.06	0.10	0.13	0.06	-0.01	0.07
IR93559A	-0.08	0.02	-0.02	0.08	0.05	0.01	-0.06	-0.03	-0.01	-0.08	-0.13
IR93560A	0.02	0.03	0.09	-0.03	-0.01	0.00	0.40*	0.39*	0.03	0.27*	0.27*
<b>LSD</b>	0.39	0.39	0.38	0.23	0.13	0.17	0.37	0.36	0.16	0.43	0.42
<b>G.M.</b>	2.91	24.34	6.89	0.69	0.36	0.99	3.77	5.81	1.00	3.76	5.80
<b>SD</b>	0.96	4.79	0.96	0.55	0.30	0.42	0.88	0.86	0.41	1.04	1.02
<b>SEM</b>	0.14	0.68	0.14	0.08	0.04	0.06	0.12	0.12	0.06	0.15	0.14
<b>S.E.</b>	0.14	0.68	0.14	0.08	0.04	0.06	0.12	0.12	0.06	0.15	0.14
<b>Best Line</b>	IR79125A	IR79125A	IR79125A	IR93559A	IR75596A	IR79125A	IR93560A	IR93560A	IR79125A	IR93560A	IR93560A
<b>Worst Line</b>	IR93559A	IR75596A	IR75596A	IR78369A	IR78369A	IR75596A	IR75596A	IR75596A	IR75596A	IR75596A	IR75596A

**Table 5B.** Estimation of the General Combining Ability (GCA) Effects of lines evaluated for drought stress at seedling stage

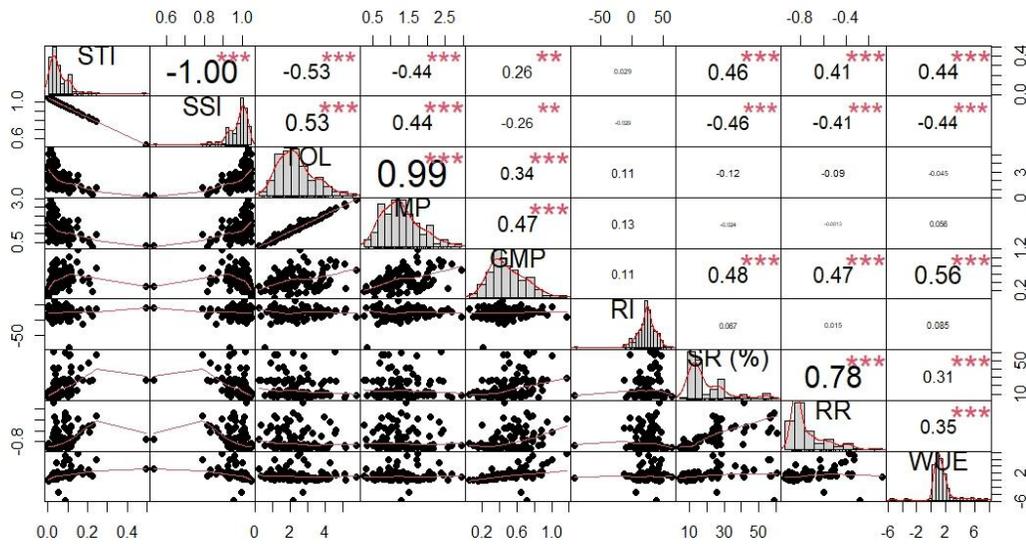
Lines	CWL_D7	CWL_D14	CWL_D21	CWL_D28	PHT_7DAP	PHT_28DAIS	PHT_REC	DBW	RL_REC	NL	RR
IR75596A	0.00	0.00	0.01	0.00	-0.06	0.12	0.15	0.01	0.55	0.23*	0.04
IR78369A	0.01	0.02*	0.03*	0.03*	1.37*	1.30*	-0.14	-0.03*	-0.41	-0.17	-0.04
IR79125A	0.00	0.00	-0.01	-0.01	0.99*	0.64*	0.01	0.00	-0.38	-0.09	-0.02
IR93559A	-0.01	-0.01	-0.01	-0.02*	-1.28*	-0.71*	0.12	0.02	0.67	0.16	0.05*
IR93560A	0.00	-0.01	-0.01	-0.01	-1.03*	-1.35*	-0.14	0.00	-0.42	-0.13	-0.03
<b>LSD</b>	0.02	0.02	0.02	0.02	1.12	1.12	0.41	0.04	1.48	0.37	0.09
<b>G.M.</b>	0.05	0.09	0.07	0.08	21.19	20.83	1.30	0.11	3.84	0.70	-0.78
<b>SD</b>	0.03	0.05	0.04	0.04	2.62	2.53	0.95	0.11	3.64	0.86	0.23
<b>SEM</b>	0.00	0.01	0.01	0.01	0.37	0.36	0.13	0.02	0.51	0.12	0.03
<b>S.E.</b>	0.00	0.01	0.01	0.01	0.37	0.36	0.13	0.02	0.51	0.12	0.03
<b>Best Line</b>	IR78369A	IR78369A	IR78369A	IR78369A	IR78369A	IR78369A	IR75596A	IR93559A	IR93559A	IR75596A	IR93559A
<b>Worst Line</b>	IR93559A	IR93560A	IR93560A	IR93559A	IR93559A	IR93560A	IR93560A	IR78369A	IR93560A	IR78369A	IR78369A

**Table 6A.** Estimation of the General Combining Ability (GCA) effects of testers evaluated for drought stress at seedling stage

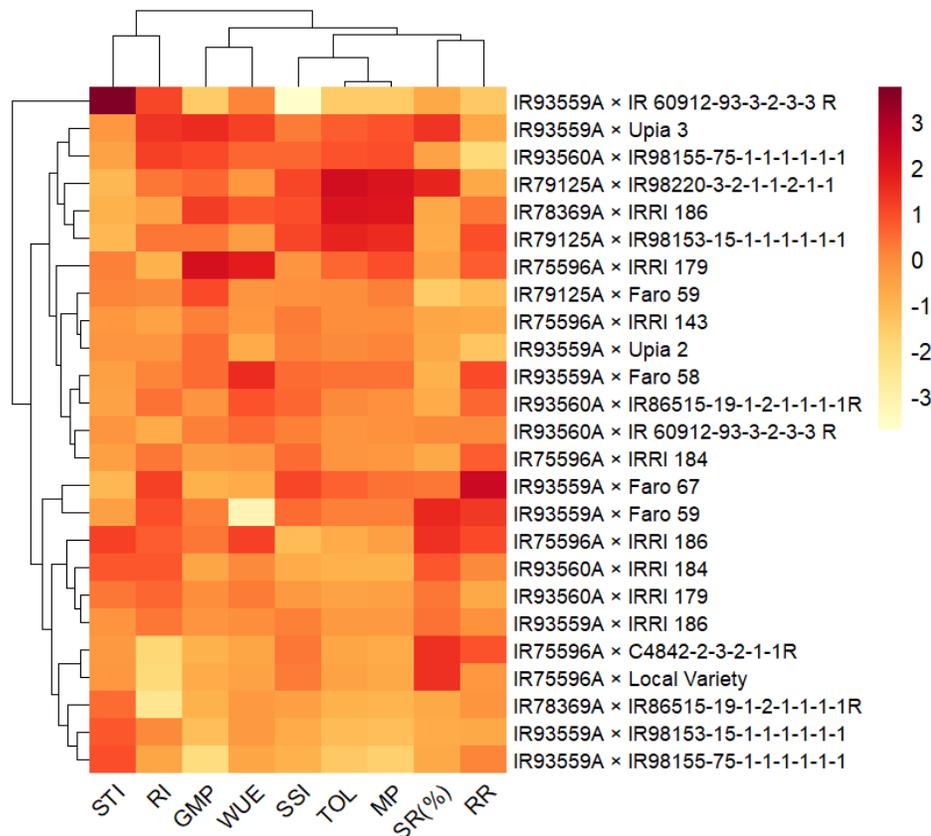
Tester	Code	DIS_7DAIS	DIS_21DAIS	DIS_28DAIS	DRS	SR (%)	LR_7DAIS	LR_21DAIS	LR_28DAIS	LD_7DAIS	LD_21DAIS	LD_28DAIS
Faro 67	C3	0.09	0.05	0.16	-0.04	0.01	0.04	0.01	-0.16	0.06	0.35	-0.04
Local Variety	C4	-0.01	0.04	0.05	-0.21	0.01	0.01	-0.25	-0.12	-0.02	-0.41	-0.24
Upia 2	C5	0.48	0.50	0.63*	0.08	0.02	0.26	0.62*	0.39	0.26	0.27	0.25
Upia 3	C6	0.25	0.23	0.22	-0.11	0.01	0.09	0.19	0.21	0.07	0.21	0.19
Faro 59	C8	0.22	0.08	0.24	0.01	0.05	0.06	0.09	0.51*	0.07	0.07	0.23
Faro 58	C9	0.37	0.39	0.47	-0.13	-0.10	0.08	0.56*	0.52*	0.07	0.39	0.42
C4842-2-3-2-1-1R	V1	0.33	0.51*	0.41	-0.17	0.01	0.16	0.20	0.10	0.16	-0.02	-0.10
IR85538-2-1-1-1-1-1-1R	V10	0.19	0.23	0.21	-0.08	-0.09	0.17	0.19	0.18	0.06	0.21	0.18
IR86515-19-1-2-1-1-1-1R	V12	0.27	0.19	0.16	0.16	0.02	0.08	-0.21	-0.16	0.10	0.23	0.18
IR86526-10-4-1-1-1-1	V14	-0.18	-0.20	-0.21	-0.01	-0.04	-0.05	-0.10	-0.15	-0.06	-0.12	-0.15
IR86612-13-1-1-1-1R	V15	0.04	0.00	-0.01	-0.15	-0.06	0.03	-0.26	-0.15	0.05	-0.39	-0.41*
IRRI 143	V17	-0.36	-0.48*	-0.50*	0.07	-0.03	-0.17	-0.21	-0.29	-0.09	-0.29	-0.18
IRRI 179	V19	-0.08	-0.09	-0.10	0.14	0.06	0.02	-0.34	-0.42*	0.01	-0.12	-0.14
IRRI 184	V22	-0.39*	-0.33	-0.40*	0.17	0.07	-0.16	-0.30	-0.50*	-0.15	-0.07	-0.10
IRRI 186	V24	-0.22	-0.32	-0.40*	0.40	0.26	-0.08	-0.30	-0.31	-0.06	-0.09	-0.14
IR112867-28-1-1	V27	-0.28	-0.22	-0.19	0.10	0.00	-0.09	0.26	0.33	-0.07	0.10	0.06
IR112898-35-1-1	V29	-0.13	-0.13	-0.25	-0.17	-0.08	-0.08	-0.13	-0.29	-0.10	-0.35	-0.35
IR 60912-93-3-2-3-3 R	V3	0.03	0.02	0.02	0.09	0.02	-0.01	0.21	0.20	-0.03	0.48*	0.43*
IR112899-11-2-1	V30	0.11	-0.11	0.01	0.15	0.00	0.02	0.10	0.16	0.03	0.34	0.16
IR101999-25-2-2	V31	0.00	-0.02	-0.03	-0.12	-0.07	0.00	0.25	0.27	0.01	0.40	0.49*
IR98145-3-2-1-1-2-1-1	V35	-0.70*	-0.55*	-0.55*	-0.28	-0.06	-0.28	0.03	-0.04	-0.30	-0.04	-0.04
IR98153-15-1-1-1-1-1-1	V36	-0.42*	-0.14	-0.32	0.16	0.00	-0.22	-0.41*	-0.39*	-0.20	-0.44*	-0.37*
IR98155-75-1-1-1-1-1-1	V37	-0.16	-0.22	-0.19	0.26	0.11	-0.09	-0.04	0.01	-0.10	-0.45*	-0.37*
IR98220-3-2-1-1-2-1-1	V43	0.21	0.15	0.14	-0.08	0.02	0.07	-0.50*	-0.24	0.07	-0.04	0.26
IR 85593-23-2-1-3-1-3-1-1-1	V6	0.36	0.44*	0.41*	-0.25	-0.12	0.13	0.34	0.33	0.15	-0.24	-0.22
<b>LSD</b>		0.87	0.87	0.84	0.51	0.29	0.37	0.82	0.81	0.37	0.95	0.95
<b>G.M.</b>		2.91	4.87	6.89	0.69	0.36	0.99	3.77	5.81	1.00	3.76	5.80
<b>SD</b>		0.91	0.91	0.92	0.54	0.30	0.40	0.85	0.83	0.39	1.01	1.00
<b>SEM</b>		0.29	0.29	0.29	0.17	0.09	0.13	0.27	0.26	0.12	0.32	0.32
<b>S.E.</b>		0.29	0.29	0.29	0.17	0.09	0.13	0.27	0.26	0.12	0.32	0.32
<b>Best Tester</b>		<b>V35</b>	<b>V35</b>	<b>V35</b>	<b>V24</b>	<b>V24</b>	<b>C5</b>	<b>C5</b>	<b>C8</b>	<b>V3</b>	<b>V3</b>	<b>V31</b>
<b>Worst Tester</b>		<b>C5</b>	<b>C5</b>	<b>C5</b>	<b>V15</b>	<b>V6</b>	<b>V36</b>	<b>V43</b>	<b>V22</b>	<b>V36</b>	<b>V37</b>	<b>V15</b>

**Table 6B.** Estimation of the General Combining Ability (GCA) Effects of testers evaluated for drought stress at seedling stage

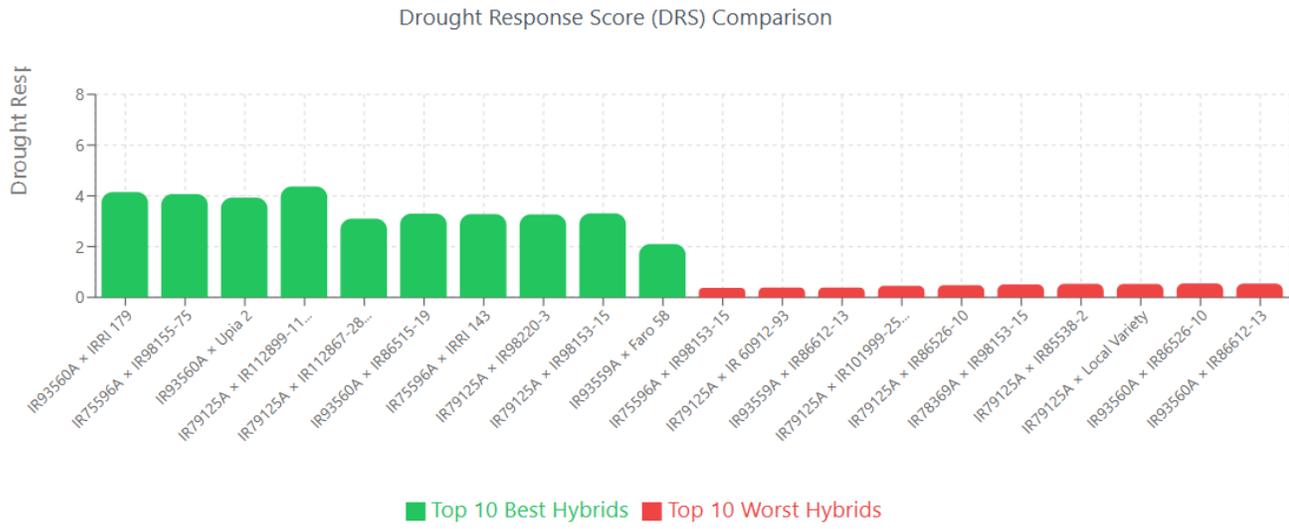
Tester	Code	CWL_D7	CWL_D14	CWL_D21	CWL_D28	PHT_7DAP	PHT_28DAIS	PHT_REC	DBW	RL_REC	NL	RR
Faro 67	C3	-0.01	-0.01	-0.01	-0.02	-1.01	-0.44	-0.06	-0.02	-0.19	0.07	0.07
Local Variety	C4	-0.01	-0.01	-0.03	-0.02	-1.19	-1.48	-0.12	-0.02	-0.40	-0.22	-0.04
Upia 2	C5	-0.01	-0.01	0.00	-0.01	0.34	-0.76	-0.11	-0.01	-0.34	-0.16	-0.06
Upia 3	C6	-0.01	0.01	0.00	0.00	0.89	-0.37	-0.19	0.01	-0.23	-0.12	-0.08
Faro 59	C8	-0.01	-0.01	-0.01	-0.01	0.51	0.45	0.03	0.03	-0.72	0.26	0.04
Faro 58	C9	0.00	0.06	0.01	0.01	-0.34	0.26	-0.07	0.00	-1.41	0.18	0.01
C4842-2-3-2-1-1R	V1	0.01	0.02	0.02	0.02	-0.24	-0.36	-0.10	-0.01	-0.88	-0.29	-0.01
IR85538-2-1-1-1-1-1-1R	V10	0.00	0.00	0.01	0.01	0.30	0.00	-0.15	-0.04	-0.15	-0.07	-0.05
IR86515-19-1-2-1-1-1-1R	V12	-0.01	-0.01	-0.01	-0.01	0.05	-1.00	0.27	0.01	1.24*	0.10	0.09
IR86526-10-4-1-1-1-1	V14	0.00	0.00	-0.02	-0.02	0.62	-0.05	0.03	0.00	0.54	-0.07	-0.02
IR86612-13-1-1-1-1-1R	V15	0.01	0.01	0.02	0.02	-1.61*	0.00	-0.16	-0.03	-0.02	-0.14	-0.04
IRRI 143	V17	0.01	-0.01	0.01	0.01	-0.33	-0.41	0.02	0.03	0.96	0.07	0.01
IRRI 179	V19	0.01	-0.01	-0.01	-0.01	0.28	-0.44	0.24	0.07	0.75	0.02	0.07
IRRI 184	V22	0.00	0.00	0.00	0.00	-0.21	0.49	0.37	0.07	0.42	0.42*	0.09
IRRI 186	V24	0.00	-0.03	-0.02	-0.02	-0.29	0.61*	0.65*	0.09	2.58*	0.84*	0.22*
IR112867-28-1-1	V27	-0.01	-0.01	0.00	0.00	0.56	0.51	0.12	0.03	0.09	-0.02	-0.03
IR112898-35-1-1	V29	0.01	0.00	0.00	0.01	-0.05	0.24	-0.21	-0.04	-0.27	0.28	-0.05
IR 60912-93-3-2-3-3 R	V3	0.01	0.02	0.02	0.02	0.18	0.58	-0.04	0.01	0.30	0.00	-0.01
IR112899-11-2-1	V30	-0.02	-0.03	-0.02	-0.02	0.34	0.66*	0.16	0.02	-0.11	-0.09	0.00
IR101999-25-2-2	V31	-0.01	-0.01	0.00	0.00	0.61	0.76*	-0.30	-0.04	-1.50*	-0.25	-0.08
IR98145-3-2-1-1-2-1-1	V35	0.01	0.01	0.01	0.01	0.43	1.69*	-0.38	-0.04	-1.33*	-0.37	-0.11
IR98153-15-1-1-1-1-1-1	V36	-0.01	-0.02	-0.02	-0.02	0.57	0.04	0.34	-0.01	1.30*	0.06	0.08
IR98155-75-1-1-1-1-1-1	V37	0.00	0.00	0.01	0.01	0.88	0.12	0.36	0.03	1.85*	0.05	0.04
IR98220-3-2-1-1-2-1-1	V43	0.01	0.01	0.02	0.02	-0.40	-0.49	-0.20	-0.07	-0.95	-0.20	-0.04
IR 85593-23-2-1-3-1-3-1-1-1	V6	0.03	0.04	0.04	0.04	-0.88	-0.63	-0.48*	-0.05	-1.53*	-0.34	-0.09
<b>LSD</b>		0.03	0.05	0.04	0.04	2.51	2.50	0.92	0.10	3.31	0.82	0.21
<b>G.M.</b>		0.05	0.09	0.07	0.08	21.19	20.83	1.30	0.11	3.84	0.70	-0.78
<b>SD</b>		0.03	0.05	0.04	0.04	2.74	2.61	0.95	0.11	3.58	0.78	0.23
<b>SEM</b>		0.01	0.02	0.01	0.01	0.87	0.83	0.30	0.04	1.13	0.25	0.07
<b>S.E.</b>		0.01	0.02	0.01	0.01	0.87	0.83	0.30	0.04	1.13	0.25	0.07
<b>Best Tester</b>		<b>V6</b>	<b>V6</b>	<b>V6</b>	<b>V6</b>	<b>V35</b>	<b>V35</b>	<b>V24</b>	<b>V24</b>	<b>V24</b>	<b>V24</b>	<b>V24</b>
<b>Worst Tester</b>		<b>V30</b>	<b>V30</b>	<b>V14</b>	<b>V14</b>	<b>V15</b>	<b>C4</b>	<b>V6</b>	<b>V6</b>	<b>V6</b>	<b>V35</b>	<b>V35</b>



**Figure 1.** Pairwise correlations and scatterplot matrix of drought stress indices in rice hybrids at seedling stage



**Figure 2.** Top 25 ranking rice hybrids identified for drought tolerance using a composite selection index



**Figure 3.** Performance of best and worse ten rice topcrosses hybrids under drought at seedling stage.

Cross combination	DIS 7DAIS	DIS 21DAIS	DIS 28DAIS	DRS	Surv. rate (%)	LR 7DAIS	LR 21DAIS	LR 28DAIS	LD 7DAIS	LD 21DAIS	LD 28DAIS	Cumul WL D7	Cumul WL D14	Cumul WL D21	Cumul WL D28	PHT 7DAP	PHT 28DAIS	PHT REC	DBW	RL REC	NL	Recovery Rate
IR75596A × Faro 67	0.01	0.35	0.09	0.21	0.05	0.11	0.17	0.81	0.17	0.10	0.52	-0.01	-0.03	-0.03	-0.03	0.94	0.53	0.39	0.11	0.04	0.02	-0.11
IR75596A × Local Variety	0.96	1.07	1.17	0.03	0.56	0.45	-0.01	-0.14	0.40	1.58	1.34	0.04	0.06	0.05	0.05	0.22	2.46	0.97	0.05	3.59	0.14	0.22
IR75596A × Upia 2	0.63	0.48	0.64	-0.21	-0.21	0.20	0.29	0.31	0.28	0.52	0.64	0.00	-0.01	-0.01	-0.01	0.67	-0.21	-0.36	-0.07	-1.70	-0.48	-0.07
IR75596A × Upia 3	0.88	1.11	0.97	-0.23	-0.18	0.42	0.99	0.80	0.42	0.57	0.88	0.02	0.00	-0.01	-0.02	1.37	0.13	-0.37	-0.10	-1.41	-0.44	-0.10
IR75596A × Faro 59	0.79	0.88	0.90	-0.21	-0.25	0.40	0.82	0.48	0.40	0.97	0.77	0.04	0.05	0.05	0.05	1.41	2.33	-0.73	-0.10	-1.85	-0.83	-0.24
IR75596A × Faro 58	0.78	0.72	0.80	-0.19	-0.12	0.03	0.31	0.44	0.07	0.65	0.77	0.03	-0.04	0.02	0.02	1.53	1.63	-0.61	-0.06	-1.30	-0.84	-0.13
IR75596A × C4842-2-3-2-1-1R	-0.52	-0.17	-0.34	0.21	0.55	-0.04	-0.09	-0.43	-0.11	-0.18	-0.03	-0.01	-0.01	0.00	0.00	-1.55	0.95	1.10	0.02	3.04	0.16	0.39
IR75596A × IR85538-2-1-1-1-1-1-1-1R	0.10	-0.01	-0.14	-0.07	-0.16	-0.10	-0.40	-0.19	0.00	-1.15	-1.12	-0.01	0.01	0.00	0.00	-0.64	-0.09	-0.36	-0.07	-2.37	-0.30	-0.12
IR75596A × IR86515-19-1-2-1-1-1-1-1R	0.14	-0.14	0.06	-0.12	-0.05	-0.05	0.35	0.60	-0.03	0.13	0.05	-0.02	-0.04	-0.03	-0.03	-0.54	1.26	-0.05	0.05	-1.55	0.04	-0.09
IR75596A × IR86526-10-4-1-1-1-1-1	0.25	0.23	0.48	-0.18	-0.20	0.20	-0.02	0.01	0.17	0.18	-0.06	0.00	0.01	0.03	0.02	0.60	-1.35	-0.50	-0.07	-1.57	-0.39	-0.15
IR75596A × IR86612-13-1-1-1-1-1R	0.14	0.18	0.12	-0.07	-0.07	0.08	0.13	0.10	0.06	-0.56	-0.69	-0.02	-0.01	-0.03	-0.03	0.71	0.67	-0.49	-0.02	-2.63	-0.41	-0.05
IR75596A × IRR1 143	-0.72	-0.55	-0.58	0.58	0.16	-0.17	-0.74	-0.82	-0.31	-0.89	-0.95	0.01	0.02	0.00	0.01	-0.80	-0.17	0.65	0.08	7.64	0.40	0.10
IR75596A × IRR1 179	0.17	0.26	0.15	0.27	0.09	0.09	0.30	0.14	0.13	1.24	1.12	0.03	0.00	-0.01	0.00	0.01	-0.56	0.64	0.26	2.55	0.59	0.28
IR75596A × IRR1 184	0.62	0.46	0.65	0.34	0.05	0.20	-0.85	-0.60	0.24	-0.81	-1.00	0.00	0.01	0.00	0.01	-3.39	-1.27	0.61	-0.03	2.47	0.33	0.26
IR75596A × IRR1 186	-0.75	-0.50	-0.53	-0.02	0.30	-0.35	0.26	0.29	-0.37	-0.02	-0.06	0.02	0.01	0.01	0.01	-2.14	-2.34	-0.03	0.15	1.68	2.56	0.19
IR75596A × IR112867-28-1-1	0.15	0.11	0.36	0.14	-0.03	0.04	-0.13	-0.12	0.29	0.09	0.41	-0.02	-0.04	-0.04	-0.04	-1.35	-1.41	0.34	0.11	0.71	-0.19	-0.02
IR75596A × IR112898-35-1-1	-0.62	-0.64	-0.71	0.39	0.29	-0.32	-1.50	-1.64	-0.28	-1.34	-1.57	0.01	0.01	0.00	0.01	0.97	-2.08	0.94	0.03	4.08	2.12	0.23
IR75596A × IR 60912-93-3-2-3-3 R	0.04	0.13	-0.07	-0.35	-0.18	0.13	-0.17	-0.25	0.17	-0.61	-0.29	0.02	0.03	0.04	0.04	-0.70	2.00	-0.65	-0.07	-3.11	-0.84	-0.13
IR75596A × IR112899-11-2-1	0.44	-0.06	0.01	0.08	0.05	0.17	0.10	0.45	-0.01	0.31	0.22	-0.01	-0.01	-0.02	-0.03	-0.23	-0.21	0.42	-0.07	-0.09	-0.04	-0.01
IR75596A × IR101999-25-2-2	-0.89	-0.86	-0.86	-0.28	-0.13	-0.41	-0.16	-0.40	-0.45	-0.70	-0.50	-0.01	0.03	0.01	0.01	0.49	0.06	-0.41	-0.05	-0.72	-0.47	-0.06
IR75596A × IR98145-3-2-1-1-2-1-1	0.85	0.53	0.72	-0.07	-0.08	0.43	-0.11	0.10	0.36	0.03	0.10	-0.02	-0.03	0.00	-0.01	-2.67	-1.43	-0.08	-0.01	-2.16	-0.23	-0.06
IR75596A × IR98153-15-1-1-1-1-1-1-1	-0.35	-0.55	-0.83	-0.60	-0.19	-0.21	0.51	0.25	-0.20	0.31	0.21	-0.02	0.00	-0.01	0.01	0.21	-1.17	-0.86	-0.05	-4.39	-0.55	-0.21
IR75596A × IR98155-75-1-1-1-1-1-1-1	-0.69	-0.63	-0.69	0.44	0.00	-0.26	0.02	0.02	-0.38	-0.68	-0.77	0.00	0.04	0.02	0.03	1.83	0.94	0.09	-0.06	0.04	-0.14	-0.03
IR75596A × IR98220-3-2-1-1-2-1-1	-1.10	-1.01	-1.16	-0.18	-0.22	-0.50	0.40	0.36	-0.44	1.09	0.85	-0.03	-0.04	-0.03	-0.05	-0.47	0.03	-0.32	-0.04	-0.66	-0.16	-0.05
IR75596A × IR 85593-23-2-1-3-1-3-1-1-1	-1.31	-1.38	-1.22	0.08	-0.03	-0.56	-0.50	-0.58	-0.57	-0.84	-0.86	-0.03	-0.01	-0.02	-0.02	3.52	-0.72	-0.33	0.03	-0.35	-0.05	-0.03

Strong + (≥1.5) Mod + (0.5-1.5) Weak + (0-0.5) Weak - (0 to -0.5) Mod - (-0.5 to -1.5) Strong - (≤-1.5) \* = Significant

Significant SCA Effects (α = 0.05, LSD-based)

IR75596A × IRR1 143 DRS: 0.58	IR75596A × IR112898-35-1-1 LR_21DAIS: -1.5	IR75596A × IR 85593-23-2-1-3-1-3-1-1-1 DRS: 0.08	IR78369A × C4842-2-3-2-1-1R Cumul_WL_D21: 0.01
IR78369A × C4842-2-3-2-1-1R Cumul_WL_D21: 0.01	IR78369A × IR112867-28-1-1 Cumul_WL_D14: 0.07	IR78369A × IR 85593-23-2-1-3-1-3-1-1-1 Cumul_WL_D7: 0.09	IR78369A × IR 85593-23-2-1-3-1-3-1-1-1-1-1-1-1 Cumul_WL_D14: 0.08
IR78369A × IRR1 184 Recovery_Rate: -0.2	IR78369A × IR98153-15-1-1-1-1-1-1-1 Recovery_Rate: -0.17	IR79125A × Faro 59 DBW: 0.21	IR79125A × IR112899-11-2-1 Cumul_WL_D7: 0.05
IR79125A × IR98153-15-1-1-1-1-1-1-1 Recovery_Rate: 0.38	IR93559A × Faro 67 Recovery_Rate: 0.58	IR93559A × Upia 3 DBW: 0.19	IR93559A × Faro 59 DBW: 0.06
IR93559A × Faro 59 Recovery_Rate: 0.4	IR93559A × Faro 58 Recovery_Rate: 0.39	IR93560A × IR 60912-93-3-2-3-3 R LR_21DAIS: -1.1	IR93560A × IR101999-25-2-2 Cumul_WL_D7: 0.04
IR93560A × IRR1 184 NL: 1.45			

Figure 4. Estimate of specific combining ability effects of rice testcross evaluated for drought stress at seedling

The negative correlations of SSI with Geometric Mean Productivity (GMP), Water Use Efficiency (WUE), Survival Rate (SR%), and Recovery Rate (RR) agrees with the work by Noguera *et al.* (2021), who reported that susceptibility indices are inversely related to integrative resilience and water-use traits under drought stress in elite breeding lines. The moderate to strong positive correlations among GMP, WUE, SR%, and RR align with the conclusions of Verma *et al.* (2024), who showed that modern drought-resilient rice genotypes combine sustained productivity with superior recovery capacity and survival. The strong association between SR% and RR ( $r = 0.78$ ) further corroborates findings by Sandhu *et al.* (2021), who identified shared genetic loci underlying post-drought survival and regrowth in rice seedlings.

### **Multivariate Discrimination of Drought-Resilient and Susceptible Hybrids**

Heatmap and cluster analyses (Figure 2) consistently identified superior and susceptible hybrid groups. Crosses such as IR93559A × IR60912-93-3-2-3-3R, IR93559A × UPIA 3, IR93560A × IR98155-75-1-1-1-1-1-1, and IR78369A × IRRI 186 exhibited high STI and GMP values alongside low SSI, indicating consistent drought-resilient profiles. This pattern agrees with Verma *et al.* (2024), who also found that superior drought-tolerant genotypes cluster together based on integrated tolerance indices. Conversely, hybrids such as IR75596A × Local Variety and IR75596A × C4842-3-2-1-IR repeatedly grouped within low-performing clusters, showing low STI and GMP with high SSI. This susceptibility profile is consistent with observations by Daryanto *et al.* (2023), where susceptible genotypes showed low productivity and high stress susceptibility across indices.

The clustering of recovery indices (RI, SR%, RR) with high-performing crosses further supports the findings of Sandhu *et al.* (2021), who identified survival and recovery as strong discriminators of drought resilience in early growth stages. The consistent performance of IR93559A × IR60912-93-3-2-3-3R across nearly all indices suggests the presence of highly favorable allele combinations for drought resilience, similar to the stable high-performing crosses reported in multi-trait evaluations by Kumar *et al.* (2022).

### **Phenotypic Variation and Physiological Dissection of Drought Response**

The mean performance analysis (Figure 3) revealed broad variability among hybrids for drought injury, leaf drying, recovery, and survival traits. Hybrids such as IR75596A × IR98153-15-1-1-1-1-1-1 and IR75596A × IR112898-35-1-1 consistently showed lower injury and reduced leaf drying, indicating strong drought avoidance. This aligns with Kumar *et al.* (2022), who reported that tolerant genotypes exhibit delayed leaf senescence and superior osmotic adjustment under prolonged stress.

In contrast, hybrids including IR79125A × IR112899-11-2-1 and IR75596A × IR98155-75-1-1-1-1-1-1 recorded superior recovery scores, corroborating Sandhu *et al.* (2021), who reported that post-drought regeneration is driven by the resilience of meristematic tissues and efficient carbon remobilization. Survival rates varied considerably, with hybrids such as IR79125A × IR98220-3-2-1-1-2-1-1, IR93559A × Faro 59, and IR75596A × IRRI 186 showing notably better survival. This agrees with Grondin *et al.* (2023), who linked high seedling-stage survival to root system architecture and sustained hydraulic conductance.

The results reveal a clear physiological and genetic decoupling between drought avoidance and recovery mechanisms. Hybrids like IR75596A × IR112898-35-1-1 excelled in avoidance (minimal symptoms), likely through stomatal or osmotic regulation, while IR93559A × Faro 67 showed moderate symptoms but exceptional recovery, indicating distinct mechanisms such as meristem protection. This confirms that drought tolerance comprises independent modules avoidance and recovery that are not necessarily correlated, as reported by Khan *et al.* (2023) and Basu *et al.* (2022). Consequently, selection based solely on visual symptoms risks eliminating genotypes with superior recovery potential.

### **General Combining Ability of Parental Lines**

General combining ability (GCA) analysis (Tables 5A, 5B, 6A, and 6B) revealed clear differentiation among parental lines for drought-responsive traits. The female line IR75596A contributed favorable additive effects for reduced leaf rolling and drying, indicating its value as a donor of drought-avoidance alleles. This aligns with Kumar *et al.* (2022), who reported that negative GCA for visual stress symptoms predicts improved drought avoidance. The

positive GCA for number of leaves further suggests improved leaf area maintenance under moisture deficit, a trait critical for sustaining photosynthetic capacity and recovery potential (Sandhu *et al.*, 2021). Conversely, IR78369A contributed favorable additive effects for plant height but unfavorable effects for survival and biomass accumulation under stress, along with increased cumulative water loss. This trade-off agrees with Panda *et al.* (2021), who observed that vigorous vegetative growth can be inversely related to drought resilience due to higher transpiration water loss.

The line IR93559A showed favorable additive effects for recovery rate and reduced water loss, revealing its usefulness in breeding for recuperative ability after stress. This supports Noguera *et al.* (2021), who emphasized that recovery rate shows significant additive genetic variance and is a heritable target for parent selection. In contrast, IR93560A contributed unfavorable additive effects for leaf rolling and drying, indicating a tendency to transmit higher visible stress symptoms, similar to patterns reported by Verma *et al.* (2024).

Among male testers, genotypes such as IRRI 143, IRRI 184, IRRI 186, and IR98145-3-2-1-1-2-1-1 showed consistently negative GCA for drought injury scores, identifying them as reliable donors of drought-tolerance alleles. This corroborates Ahmed *et al.* (2023), who found that testers with stable negative GCA for stress-injury traits are valuable in hybrid breeding programs. In contrast, testers such as UPIA 2 and C4842-2-3-2-1-1R exhibited positive GCA for drought injury in certain stages, indicating unfavorable additive contributions. The strong additive effects for recovery traits observed in IRRI 186 align with Sandhu *et al.* (2021), who identified recovery capacity as a highly heritable trait governed primarily by additive gene action in rice. This positions IRRI 186 as a promising tester for introgression recovery-related traits.

### **Specific Combining Ability and Hybrid Performance**

Specific combining ability (SCA) analysis (Figure 4) revealed that non-additive genetic effects predominantly govern drought tolerance and recovery. Hybrids with favorable SCA exhibited superior performance, indicating the importance of dominance and epistasis for resilience. This aligns with Kumar *et al.* (2022), who found that SCA is more important than GCA for complex physiological traits like water-use efficiency under stress.

The cross IR75596A × IRRI 143 showed strong positive SCA for drought response score and root length recovery, indicating exceptional parental complementarity and the importance of non-additive gene action in drought tolerance expression (Kumar *et al.*, 2022). For leaf rolling, crosses such as IR75596A × IR112898-35-1-1 showed significant negative SCA at 21 DAIS, indicating improved tolerance through reduced leaf rolling under stress, consistent with reports that dominance and epistasis regulate leaf water status maintenance in rice (Panda *et al.*, 2021). Hybrids including IR93560A × IRRI 184 displayed positive SCA for new leaf production, indicating non-additive control of post-stress vegetative recovery and metabolic reactivation (Sandhu *et al.*, 2021). Similarly, IR78369A × IR85538-derived hybrids showed favorable SCA for recovery-associated biomass traits, suggesting dominance-driven plasticity in drought adaptation, in agreement with evidence that drought-responsive growth recovery is largely governed by non-additive genetic interactions (Khan *et al.*, 2023). Contrasting SCA directions for water conservation traits among hybrids reflect the complex genetic control of stomatal regulation, supporting Grondin *et al.* (2023), who reported that water-use traits are highly polygenic and influenced by specific interactions.

Hybrids such as IR93559A × Faro 67 showed positive SCA for recovery rate, while others like IR78369A × IRRI 184 showed negative SCA. This divergence confirms the conclusions of Coulter *et al.* (2022), who reported that recovery is a genetically distinct and complex trait, with performance highly specific to parental combination. These results confirm that drought resilience in this population is best exploited through hybrid breeding, as superior performance depends critically on specific parental combinations rather than average parental value. These combining ability patterns are particularly relevant for Nigeria, where hybrid rice development remains constrained by stress instability and limited locally adapted parental lines.

### **Conclusion**

This study clarified the genetic control of seedling-stage drought tolerance in 125 rice topcross hybrids and identified breeding-relevant traits, parents, and hybrid combinations. Morphological avoidance traits, particularly leaf rolling and leaf drying showed measurable additive genetic variance and moderate narrow-sense heritability, indicating suitability for direct selection in inbred breeding. In contrast,

drought recovery score, survival rate, and root length at recovery exhibited negligible additive variance but strong specific combining ability effects, confirming the predominance of non-additive gene action and the need for hybrid-based improvement of seedling resilience. General combining ability analysis identified IR75596A as a key donor for drought avoidance through reduced leaf rolling and drying, while testers IRRI 186 and IRRI 184 contributed favorable alleles for recovery and root traits. Multivariate and mean performance analyses

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