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RESEARCH ARTICLE

Genetic analysis of rice hybrids for early seedling vigour under anaerobic and non-stress conditions

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Abstract

Anaerobic germination (AG) tolerance is critical for enhancing seedling establishment in direct-seeded rice (DSR), especially in flood-prone lowland ecosystems. This study investigated the genetic basis of AG tolerance in rice hybrids for Nigerian lowland ecosystems. The study evaluated 125 F_1 rice hybrids derived from five cytoplasmic male sterile (CMS) lines and 25 restorer lines using a line × tester design under both anaerobic and non-stress conditions. Significant genetic variation was observed for key traits, including germination percentage, seedling vigour index, plant height and root length. Broad-sense heritability ranged from moderate to high (h^2b = 0.33–0.84) across most of the traits measured, with negligible values for fresh and dry biomass weight. General combining ability (GCA) analysis identified IR93560B, IR93559B, IR75596B and the tester UPIA 3 as superior parents with significant positive effects across multiple germination stages. Specific combining ability (SCA) analysis revealed that hybrids IR93559B × IRRI 143 and IR75596B × IR98153-15-1-1-1-1-1-1 exhibited consistently high germination rate under anaerobic and control conditions (both 100%). Strong positive correlations were detected between germination percentage and SVI, and between plant height and root length, supports the use of these traits in the selection of hybrids. Principal component analysis showed PC1 accounted for 50% and PC2 for 15% of total phenotypic variance. The study reveals the potential of specific CMS-restorer combinations for developing AG-tolerant rice hybrids, thus providing valuable information for breeding programs targeting climate-resilient, direct-seeded rice systems in Nigeria and beyond.

Keywords: Anaerobiosis, heritability, hybrids, rice, vigour

Introduction

Flooding is a major constraint to rice production in lowland ecosystems, impairing seed germination, crop establishment, and yield stability (Septiningsih *et al.*, 2009; Ismail *et al.*, 2012). In Africa, where direct seeding is common, poor germination due to inundation is particularly devastating (Kuya *et al.*, 2019). Globally, irrigated rice ecosystems account for 55% of cultivated area and 75% of rice production, but productivity is increasingly threatened by soil degradation, declining water tables, and climatic variability (Mahender *et al.,* 2015; Muvendhan *et al.,* 2023). Rainfed lowland and deep-water rice systems, covering ~50 million hectares, represent one-third of the global rice area and remain highly vulnerable to flooding stress (Oladosu *et al.,* 2020).Direct-seeded rice (DSR) is being promoted as a sustainable alternative to transplanting because it saves labour and water, reduces production costs, improves soil health, and lowers greenhouse gas emissions (Wu and Zeng, 2017; Verma and Sandhu, 2024). However, crop establishment in DSR is constrained by flooding during germination. Anaerobic germination (AG) is therefore a critical trait, enabling seedlings to emerge and establish under submerged conditions. Rice genotypes with AG tolerance display improved stand establishment, seedling vigour, and yield stability, making the trait particularly important for climate-resilient rice production (Mohanty, 2022).Hybrid rice, with its superior yield potential, can further benefit from AG tolerance. Incorporating this trait strengthens seedling survival under submergence, reduces establishment failures, and promotes uniform plant stands. In Nigeria, where labour shortages, water scarcity, and recurrent flash floods limit rice productivity, AG-tolerant hybrids can play a key role in enhancing resilience and ensuring food security. Furthermore, the integration of AG tolerance into hybrid development supports the adoption of DSR and stimulates the seed system by enabling the dissemination of stress-resilient varieties adapted to local conditions. To develop such hybrids, it is essential to evaluate genetic variability and estimate combining ability effects of parental lines. These analyses help identify superior parents and cross combinations for seedling vigour traits, providing insights into the inheritance of AG tolerance and informing targeted breeding strategies (Septiningsih *et al.*, 2009; Verma and Sandhu, 2024). Despite its importance, the deployment of AG-tolerant hybrids in Nigeria has been limited due to narrow donor pools and inadequate screening facilities. The present study was therefore undertaken to evaluate the performance of rice hybrids for early seedling vigour under both anaerobic (stress) and non-stress conditions then to assess the extent of genetic variability for AG-related traits, specific combining abilities of parental lines; and to identify promising hybrids with superior seedling vigour suited for DSR in flood-prone environments.

Materials and methods

A total of 125 rice hybrids were developed using the line × tester mating design, where five cytoplasmic male sterile (Maintainer or B-lines) served as female parents and were crossed with a set of 25 male testers (comprising 19 restorer lines and 6 commercial varieties) Table 1. The 125 hybrids, along with their parents (5 B-lines, 19 restorer lines, and 6 commercial varieties), were evaluated for anaerobic germination (AG) tolerance at the seedling stage under controlled greenhouse conditions at the National Cereal Research Institute (NCRI), Badeggi (Lat. 9.076847^{o} and long. 6.046724). For the AG screening, one seed per entry was sown in a 1.5 × 1.5 × 2 cm grid cell on plastic trays (dimension: 38 × 53 cm) labeled appropriately. Each genotype was sown in two rows with 17 seeds per row, following a randomized complete block design (RCBD) with three replications. The total number of seeds sown per entry was documented. To simulate anaerobic conditions, the seeded trays were submerged in large containers filled with water to a height of 10 cm above the soil surface, while trays designated as controls were maintained at 3 cm water depth. The number of surviving seedlings was recorded at three-day intervals, starting from nine days after sowing (DAS) and continued through 12 days of submergence, following standard AG screening protocols (IRRI, 2021). The water quality parameters were measured under anaerobic germination (AG) and control conditions (Table 2).

Similarly, physicochemical properties of the soil at the experimental site prior to anaerobic germination trial was analyzed (Table 3). Observations were recorded after 21 days of submergence. Initial number of seeds sown for each genotype was recorded immediately after seeding, as well as the number of surviving seedlings 14 and 21 days after seeding. This latter measurement, was termed 'number of seeds germinated' and was referred to those seedlings that emerged above the water surface. Percentage germination (survival) served as the primary determinant for identifying flood-tolerant cultivars, and it was calculated using the formula:

$$Percentage\ Germination = \frac{(Number\ of\ seeds\ germinated\ per\ entry)}{(Total\ seeds\ sown\ per\ entry)} \times 100$$

In an attempt to enhance the identification of robust flood-tolerant donors, data collection will be expanded to include additional growth parameters. These parameters will encompass seedling height (cm) and Root length (cm), which was measured 14 and 21 days after seeding using a standard ruler. To complete the assessment, sampled seedlings was harvested and subjected to drying at 70°C for three days to measure fresh and biomass weigh (g) using a sensitive weigh scale. Seedling vigour index was calculated using the formula as suggested by Abdul-Bakiand Anderson (1973) expressed in the whole number. Seedling vigor index (SVI) = Germination (%) × Seedling length (cm). The difference among the genotypes was tested by ANOVA using SAS version 9.13 (SAS Institute, 2011). Fisher's least significant difference (LSD) test (α = 0.05) was used to separate the means.

Table 1. List of B and R lines evaluated for anaerobic germination tolerance

Sr. No.	Designation	Type	Origin	Ecotype
1	IR75596B	Maintainer Line	IRRI	Indica
2	IR78369B	Maintainer Line	IRRI	Indica
3	IR79125B	Maintainer Line	IRRI	Indica
4	IR93559B	Maintainer Line	IRRI	Indica
5	IR93560B	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

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Table 2: Summary of water quality parameters measured under anaerobic germination (AG) and control conditions

Parameter	Treatment	Mean ± SD	Min–Max
Conductivity (µS/cm)	Control	642.8 ± 825.6	114.6–2830
Conductivity (µS/cm)	AG	1960.3 ± 528.4	108–2624
pH	Control	8.75 ± 0.57	7.0–9.91
pH	AG	9.17 ± 0.45	7.04–10.11
Temperature (°C)	Control	26.7 ± 4.7	8.81–34.6
Temperature (°C)	AG	26.1 ± 4.3	18.2–32.9

Table 3: Physicochemical properties of the soil at the experimental site prior to anaerobic germination trial

(Mg/kg)	pH	Percentage			µS/cm	Cmol/kg					µS/cm	Cmol/kg	Percentage			
	H_2O	OC	OM	N	E.C	Na	K	Ca	Mg	H + Al	40 sec.	2 hrs.	Clay	Silt	Sand	Textural Class
33.8	7.2	0.4	0.7	0.0	0.1	0.2	0.2	4.0	1.2	0.4	21	3	10	36	54	SL
11.3	7.1	0.3	0.6	0.1	0.1	0.1	0.2	2.2	0.7	0.4	22	3	10	38	52	SL
11.3	7.0	0.3	0.6	0.1	0.1	0.1	0.2	4.0	1.2	0.4	21	3	10	36	54	SL

Results and discussion

Mean squares of analysis of variance for line × tester under water stress condition revealed significant genetic variation across traits (Table 4). Germination at seven days after sowing showed significant ($p < 0.05$) differences for parents by crosses interaction and tester effects, while lines revealed highly ($p < 0.01$) significant differences. Germination at 14 and 21 days after sowing (DAS) demonstrated highly ($p < 0.01$) significant differences for treatments, parents, crosses, lines, testers and line by tester interaction. Plant height (PHT) showed highly ($p < 0.01$) significant differences for treatments, parents, crosses, tester and line by tester interaction. Root length (RL) exhibited highly ($p < 0.01$) significant differences for treatments, crosses and line by tester interaction. Fresh biomass weight (FBW) showed no significant differences across all sources of variation, while dry biomass weight (DBW) was significant only for parents. Germination percentage (Germ%) and seedling vigour index (SVI) displayed highly ($p < 0.01$) and ($p < 0.05$) significant differences respectively across most sources of variation.

The ANOVA results under anaerobic germination (AG) and control conditions revealed varying levels of genetic control across treatments. These findings corroborate those of El-Mouhamady *et al.*, (2022), who reported significant genetic variation among rice hybrids under water stress conditions. The significant mean squares for germination traits align with reports by Patil (2011) and Prajapati (2013) using line × tester analysis in rice. The limited response of fresh biomass weight suggests minimal immediate response to early anaerobic conditions, while the significant parental effects on dry biomass weight implies heritable components in biomass accumulation under stress, similar to findings by El-Mouhamady *et al.*, (2022).

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GCA effects analysis revealed important genetic potential among parents for anaerobic germination traits (Table 5). Line IR93560B exhibited significant positive GCA effects (0.01) for germination at seven DAS. Testers IR98220-3-2-1-1-2-1-1 and UPIA 3 showed positive significant GCA effects (0.58) for seven-day germination. Faro 67 and UPIA 3 demonstrated positive significant GCA effects (1.73 and 3.07) for fourteen-day germination, while UPIA 3 maintained positive significant effects (2.20) for twenty-day germination. Tester IR112899-11-2-1 exhibited negative but significant GCA effects (-5.48) for plant height, while IR 60912-93-3-2-3-3 R and UPIA 2 showed highly significant positive GCA effects (6.01 and 5.61) for fresh and dry biomass weight respectively. The positive GCA effects observed for IR93560B align with findings by Abe *et al.,* (2018), who identified similar effects in japonica lines for early anaerobic germination. The exceptional performance of UPIA 3 across multiple germination time points suggests possession of multiple QTLs for sustained anaerobic tolerance, similar to findings by Angaji *et al.*, (2010). The negative GCA effect for plant height in IR112899-11-2-1 contrasts with positive correlations reported by Septiningsih *et al.*, (2013), suggesting independent inheritance patterns as proposed by Baltazar *et al.,* (2014). The significant positive GCA effects for biomass traits corroborate findings by Magneschi and Perata (2009),

Table 4: Mean squares from line x tester analysis of rice topcrosses under water stress condition

Source of variation	Df	Days after sowing			Plant height (cm)	Root lenght (cm)	Fresh biomass weight (g)	Dray biomass weight (g)	Germniation (%)	Seedling vigour index
		7	14	21						
Replication	2	2.2	7.2	207.2	3341.4	159.0	21.1	13.0	21893.9	2336901.8
Treatments	154	0.4^{NS}	8.6**	10.6**	57.9**	14.2**	19.2^{NS}	23.4^{NS}	1203.4**	93754.3**
Parents	29	0.1^{NS}	9.4**	10.9**	61.9**	11.8^{NS}	0.0^{NS}	37.9*	1093.1**	81965.6*
Parents vs cross	1	1.7*	-11.1^{NS}	-47.2^{NS}	-384.7^{NS}	-216.5^{NS}	3.9^{NS}	11.5^{NS}	290.5^{NS}	456.3^{NS}
Cross	124	0.5^{NS}	8.5**	11.0**	60.6**	16.6**	23.8^{NS}	20.2^{NS}	1236.5**	97263.7**
Lines	4	1.9**	43.0**	50.4**	78.2^{NS}	24.7^{NS}	23.7^{NS}	20.0^{NS}	5065.9**	427676.3**
Tester	24	0.7*	16.7**	17.5**	94.0*	22.7^{NS}	23.6^{NS}	20.5^{NS}	1773.7*	116882.7^{NS}
Line x tester	96	0.4^{NS}	5.0*	7.7**	51.5**	14.8**	23.8^{NS}	20.1^{NS}	942.7**	78591.8*
Error	303	0.4	3.7	4.1	31.0	8.2	19.5	24.0	592.9	54374.1

indicating additive gene control for biomass accumulation under anaerobic conditions. SCA analysis of 125 crosses revealed significant genetic interactions (Table 5). Notable positive SCA effects included IR75596B×IR98220-3-2-1-1-2-1-1 and IR75596B×UPIA 3 (0.96 each) for seven-day germination. IR75596B×IRRI 186 (2.44) and IR93559B×IRRI 143 (3.32) showed significant positive effects for fourteen-day germination. For twenty-one-day germination, IR75596B×IR98153-15-1-1-1-1-1-1 (2.99) and IR93559B×IRRI 143 (3.31) exhibited positive significant effects. Plant height showed significant positive SCA in IR78369B×IR112899-11-2-1 (8.59) and IR79125B×IR101999-25-2-2 (9.22). Root length demonstrated positive effects in similar crosses. Germination percentage revealed exceptional SCA in IR93560B×IR98155-75-1-1-1-1-1-1 (64.07), while seedling vigour index showed remarkable effects in IR93560B×IR98155-75-1-1-1-1-1-1 (725.07).

The significant positive SCA effects align with findings by Ella *et al.,* (2011), who reported exceptional hybrid performance due to complementary gene interactions during early anaerobic germination. The variation in SCA effects across germination stages supports findings by Li *et al.,* (2023) regarding stage-specific gene expression patterns. The contrasting SCA effects for biomass traits demonstrate complex epistatic interactions described by Colmer *et al.,* (2014), supporting their hypothesis of multiple interacting loci with parent-specific effects. Variance component analysis revealed substantial genetic variability across traits (Table 6). Additive genetic variance (σ^2A) ranged from 0.08 to 2.50 for early seedling vigour traits, while dominance variance (σ^2D) was particularly high for twenty-one-day germination (4.91), indicating non-additive gene action contributions at later growth stages. Broad-sense heritability was moderate to high (h^2b = 0.33–0.84) for germination traits. Plant height, root length, germination percentage, and seedling vigour index displayed appreciable additive and dominance variances, with dominance variance especially pronounced in plant height (σ^2D = 31.29) and SVI (σ^2D = 29287.13). Heritability estimates were consistently high (h^2b = 0.70–0.79). Fresh and dry biomass weights exhibited negligible genetic variances with near-zero *et al.,* (2019), who reported significant dominance effects during early seedling development under anaerobic conditions. High broad-sense heritability estimates are consistent with observations by Quilloy *et al.,* (2020) for anaerobic germination tolerance. The genetic variability patterns observed in our study are further supported by Rathia *et al.,* 2025), who documented significant genetic variation and heritability estimates for seedling vigour traits in rice, emphasizing the potential for genetic improvement through selection. The high dominance variance for plant height and SVI agrees with findings by Muvendhan *et al.,* (2023), suggesting both additive and non-additive genetic effects influence these traits. The negligible genetic variances for biomass traits are consistent with Quilloy *et al.,* (2020), indicating limited responsiveness to selection for these traits under anaerobic conditions.

Table 6: Estimates of genetic parameters for anaerobic germination traits in rice top crosses

Variance component	Days after sowing			Plant height (cm)	Root length (cm)	Fresh biomass weight (g)	Dry biomass weight (g)	Germination (%)	Seedling vigour index
	7	**14**	**21**						
σ^2Line	0.0	0.5	0.6	0.3	0.2	0.0	0.0	55.0	4654.5
σ^2Tester	0.0	0.8	0.5	2.3	0.4	0.0	0.0	55.4	2553.8
σ^2Line×T	0.0	0.5	1.2	7.8	2.0	0.0	0.0	108.7	7321.8
σ^2GCA	0.0	0.6	0.5	1.4	0.3	0.0	0.0	55.2	3508.7
σ^2A	0.1	2.5	2.2	5.5	1.1	0.0	0.0	220.9	14034.7
σ^2D	0.0	1.8	4.9	31.3	8.0	0.0	0.0	434.7	29287.1
σ^2E	0.2	1.2	1.3	9.5	2.4	8.1	6.9	205.6	18876.6
h^2b	0.3	0.8	0.8	0.8	0.8	0.0	0.0	0.8	0.7

Performance evaluation of rice topcrosses revealed wide variability among crosses (Table 7 a and b). Superior early growth was observed in crosses like IR75596B × IR98153-15-1-1-1-1-1-1 (8.67 at 21DAS) and IR78369B × UPIA 3 (7.33 cm at 21DAS).

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Plant height ranged significantly from 0.83 cm (IR78369B × Faro 58) to 17.33 cm (IR78369B × UPIA 3). Root length analysis revealed exceptional performance in IR78369B× IR98145-3-2-1-1-2-1-1 (9.62 cm) and IR78369B × IR98220-3-2-1-1-2-1-1 (9.13 cm), while IR79125B × IRRI 186 exhibited shorter roots (2.00 cm). High germination percentages (>70%) were noted in IR75596B ×IR98153-15-1-1-1-1-1-1(86.67%), IR75596B × IR86612-13-1-1-1-1R (76.67%), and IR78369B × UPIA 3 (73.33%). Seedling vigour index was highest in IR75596B × IR98153-15-1-1-1-1-1-1 (637.88) and IR78369B × UPIA 3 (552.00). The observed variability agrees with Yamauchi and Winn (1996), who reported significant differences in seedling vigour among rice cultivars under anaerobic conditions. Plant height variation is consistent with observations by Asante *et al.*, (2021) regarding genotypic differences under low-oxygen conditions. Root length findings align with studies emphasizing root importance in anaerobic seedling establishment. High germination percentages corroborate findings by Asante *et al.*, (2021) regarding genetic variability in anaerobic germination rates. Evaluation of 125 F_1 hybrid crosses under anaerobic and control conditions revealed significant genotypic variability (Fig.1 and 2). Under anaerobic conditions, germination percentages ranged from 60% to 95%, with IR93559B×IRRI 143 exhibiting the highest rate (95%). Control conditions showed uniformly high germination (90-100%). IR93559B × IRRI 143 emerged as the most consistent performer across environments (95% AG, 100% control). Correlation analysis revealed strong positive associations among traits (Fig. 3). Highly significant correlations were observed between 14 DAS and 21 DAS (r=0.90**), germination percentage and seedling vigour index (r=0.95**), and 21 DAS with both germination percentage (r=0.96**) and SVI (r=0.91**). Moderate to strong positive correlations were found between root length and plant height (r=0.77**), and moderate positive correlations between plant height and germination percentage (r=0.48*). The strong correlations between germination traits align with studies by Ghosal *et al.*, (2019) regarding consistent performance across time points. The positive relationship between germination percentage and seedling vigour index supports findings by Mwakyusa *et al.*, (2023), emphasizing their importance in breeding programs. The correlation between morphological traits reflects coordinated shoot-root development crucial for nutrient uptake in flooded soils.

Fig 1: Germination performance of best and worse ten rice top crosses hybrids under Anaerobic germination condition

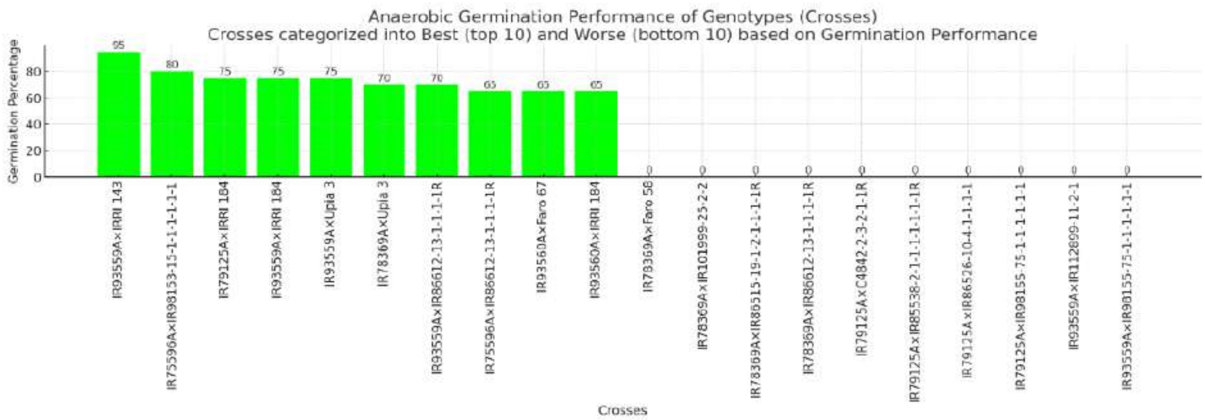

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Fig 2: Germination performance of best and worse ten rice top crosses hybrids under controlled condition

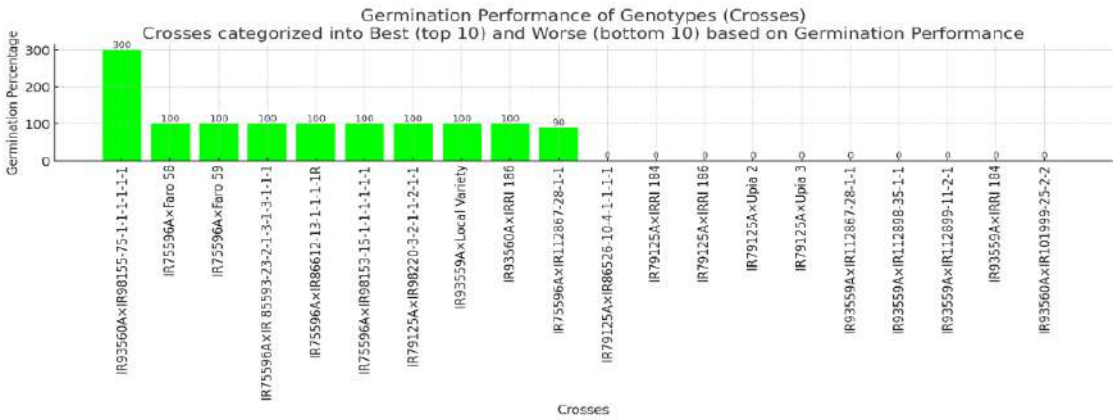

Table 7a: Mean performance of rice topcross under the anaerobic germination condition

Trait	Category	Rank	Cross	Value
7 Days after sowing	**Best**	1	IR75596A×IR98220-3-2-1-1-2-1-1	2.0
		1	IR75596A×UPIA 3	2.0
	Worst	1	IR75596A×C4842-2-3-2-1-1R	0.0
		1	IR75596A×IR 60912-93-3-2-3-3 R	0.0
14 Days after sowing	**Best**	1	IR78369A×UPIA 3	6.0
		1	IR75596A×IR98153-15-1-1-1-1-1-1	6.0
	Worst	1	IR78369A×IR86515-19-1-2-1-1-1-1R	0.0
		1	IR78369A×IR101999-25-2-2	0.0
21 Days after sowing	**Best**	1	IR75596A×IR98153-15-1-1-1-1-1-1	8.7
		2	IR75596A×IR86612-13-1-1-1-1R	7.7
	Worst	1	IR78369A×IR86515-19-1-2-1-1-1-1R	0.0
		1	IR78369A×IR101999-25-2-2	0.0
Plant height (cm)	**Best**	1	IR78369A×UPIA 3	17.3
		1	IR78369A×Faro 59	17.3
	Worst	1	IR78369A×IR86515-19-1-2-1-1-1-1R	0.0
		1	IR78369A×IR101999-25-2-2	0.0
Root lenght (cm)	**Best**	1	IR78369A×IR98145-3-2-1-1-2-1-1	9.6
		2	IR78369A×IR98220-3-2-1-1-2-1-1	9.1
	Worst	1	IR78369A×IR86515-19-1-2-1-1-1-1R	0.0
		1	IR78369A×IR101999-25-2-2	0.0
Fresh biomass weight (g)	**Best**	1	IR79125A×IR112867-28-1-1	0.3
		2	IR75596A×IR112867-28-1-1	0.3
	Worst	1	IR78369A×IR86515-19-1-2-1-1-1-1R	0.0
		1	IR78369A×IR101999-25-2-2	0.0
Dry biomass weight (g)	**Best**	1	IR75596A×UPIA 2	0.3
		2	IR75596A×IR98145-3-2-1-1-2-1-1	0.1
	Worst	1	IR78369A×IR86515-19-1-2-1-1-1-1R	0.0
		1	IR78369A×IR101999-25-2-2	0.0
Germination (%)	**Best**	1	IR75596A×IR98153-15-1-1-1-1-1-1	86.7
		2	IR75596A×IR86612-13-1-1-1-1R	76.7
	Worst	1	IR78369A×IR86515-19-1-2-1-1-1-1R	0.0
		1	IR78369A×IR101999-25-2-2	0.0
Seedling vigour index	**Best**	1	IR75596A×Faro 58	665.5
		2	IR75596A×IR98153-15-1-1-1-1-1-1	637.9
	Worst	1	IR78369A×IR86515-19-1-2-1-1-1-1R	0.0
		1	IR78369A×IR101999-25-2-2	0.0

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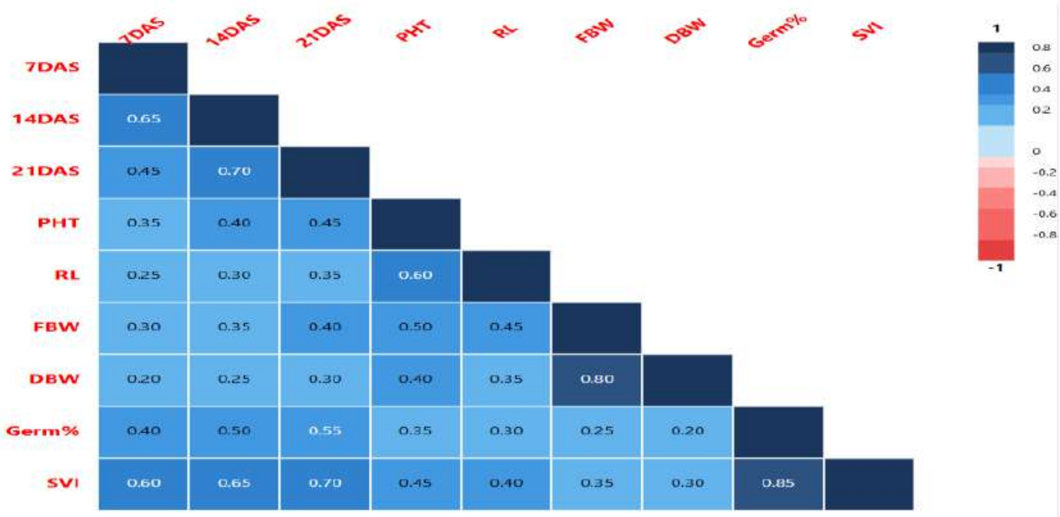
Table 7b: Mean performance of rice topcross under the bAnaerobic germination and controlled condition

Trait	Category	Rank	Cross	Value
7 Days after sowing	**Best**	1	IR79125A×IR98220-3-2-1-1-2-1-1	1.7
		1	IR93559A×IR 85593-23-2-1-3-1-3-1-1-1	1.3
	Worst	1	IR93559A×IR112899-11-2-1	0.0
		1	Multiple crosses (45+ crosses)	0.0
14 Days after sowing	**Best**	1	IR79125A×UPIA 3	7.0
		1	IR93559A×IRRI 143	6.3
	Worst	1	IR79125A×IR98155-75-1-1-1-1-1-1	0.0
		1	IR93559A×IR112899-11-2-1	0.0
21 Days after sowing	**Best**	1	IR93559A×IRRI 143	8.3
		2	IR93560A×IR112898-35-1-1	6.7
	Worst	1	IR93559A×IR112899-11-2-1	0.0
		1	IR93560A×IR98153-15-1-1-1-1-1-1	0.7
Plant height (cm)	**Best**	1	IR93560A×IR 85593-23-2-1-3-1-3-1-1-1	17.1
		1	IR93559A×IR 85593-23-2-1-3-1-3-1-1-1	16.7
	Worst	1	IR93559A×IR112899-11-2-1	0.0
		1	IR93560A×IR101999-25-2-2	0.0
Root lenght (cm)	**Best**	1	IR93560A×UPIA 2	9.6
		2	IR93559A×IR98153-15-1-1-1-1-1-1	9.6
	Worst	1	IR93559A×IR112899-11-2-1	0.0
		1	IR93560A×IR101999-25-2-2	0.0
Fresh biomass weight (g)	**Best**	1	IR79125A×Local Variety	0.4
		2	IR79125A×UPIA 3	0.3
	Worst	1	IR93559A×IR112899-11-2-1	0.0
		1	IR93560A×IR101999-25-2-2	0.0
Dry biomass weight (g)	**Best**	1	IR79125A×UPIA 2	29.0
		2	IR79125A×Local Variety	0.1
	Worst	1	IR93559A×IR112899-11-2-1	0.0
		1	IR93560A×IR101999-25-2-2	0.0
Germination (%)	**Best**	1	IR93560A×IR98155-75-1-1-1-1-1-1	110.0
		2	IR93559A×IRRI 143	83.3
	Worst	1	IR93559A×IR112899-11-2-1	0.0
		1	IR93559A×IR112898-35-1-1	3.3
Seedling vigour index	**Best**	1	IR93560A×IR98155-75-1-1-1-1-1-1	1130.0
		2	IR93560A×UPIA 2	694.1
	Worst	1	IR93559A×IR112899-11-2-1	0.0
		1	IR93560A×IR101999-25-2-2	0.0

Fig 3: Correlation matrix showing association between anaerobic germination traits



In conclusion the present study revealed a significant genetic variability among rice hybrids for early seedling vigour traits under both anaerobic and non-stress conditions. The presence of highly significant general and specific combining ability effects indicates the influence of both additive and non-additive gene actions in the expression of these traits. Dominance variance played a major role in traits like seedling vigour index and plant height, while traits such as germination percentage and root length exhibited high broad-sense heritability, making them reliable for selection in breeding programs. Also, certain crosses, such as IR93559B × IRRI 143, IR75596B × IR98153-15-1-1-1-1-1-1, and IR78369B × UPIA 3, consistently performed well across anaerobic and control conditions, revealing their potential as elite candidates for developing flood-tolerant, direct-seeded rice (DSR) varieties. Additionally, some cytoplasmic male sterile (CMS) lines like IR93559B, IR75596B, and IR93560B showed strong combining ability effects, making them valuable for hybrid development. The strong positive correlations between germination percentage, seedling vigour index, and other early growth traits further validate their utility as selection indices in rice breeding for anaerobic germination tolerance. Based on these findings, breeding programs should prioritize the development of hybrids combining high AG tolerance and robust seedling vigour to support DSR adoption in flood-prone ecologies. Promising combinations such as IR93559B × IRRI 143 and IR75596B × IR98153-15-1-1-1-1-1-1 suggest advancement to multi-location trials for performance validation. Parental lines with favorable GCA effects, particularly UPIA 3 and IR93560B, should be incorporated into hybrid seed production pipelines. Selection strategies should focus on highly heritable traits like germination percentage, SVI, and root length, while genomic tools such as marker-assisted selection and genomic prediction could enhance the efficiency of breeding for complex AG-related traits.

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