



RESEARCH ARTICLE

Exploring heterotic potential and combining ability of elite rice varieties for enhanced agricultural productivity

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Abstract

This study was conducted at the College of Agriculture, Indira Gandhi Krishi Vishwavidyalaya (IGKV), Raipur, Chhattisgarh, India, during the kharif seasons of 2021 and 2022 to assess the combining ability and heterotic potential of rice genotypes using a line × tester mating design. Three superior rice varieties, namely Rajeshwari, Mahamaya and IGKV R 1244, were crossed with four indigenous testers (IC0491194, IC0496940, IC0491254 and IC0558317), generating 12 hybrids that were evaluated for yield and yield-attributing traits. Analysis of variance (ANOVA) revealed significant treatment variation across most traits, confirming adequate genetic diversity among the experimental materials. Both additive and non-additive gene actions were found to govern trait expression, suggesting that both selection-based approaches and hybrid breeding programmes could be effectively utilised for trait improvement. Rajeshwari and IGKV R 1244 emerged as superior general combiners for yield and yield-attributing traits, while IC0558317 proved to be a promising tester for productivity-related characters. Among the hybrid combinations, IGKV R 1244 × IC0558317, Rajeshwari × IC0491254 and Mahamaya × IC0491254 were identified as superior specific combiners for seed yield per plant. Notable mid-parent heterosis was recorded for grain yield in crosses such as Rajeshwari × IC0558317 (47.66 %) and IGKV R 1244 × IC0558317 (47.46 %), underscoring their potential for commercial hybrid development. The study further highlights the value of Rajeshwari and IGKV R 1244 as promising parental lines for hybrid development.

Keywords: general combining ability; heterosis; line × tester; rice; specific combining ability; yield

Introduction

Rice (*Oryza sativa* L.) is a major staple food for more than half of the world's population and it accounts for 21 % of global dietary energy, 14 % of protein and 2 % of fat intake (1, 2). The global population is increasing rapidly and is projected to reach approximately 10 billion by 2050 (3). Climate change and the reduction in arable land are adversely affecting crop production (4). India cultivates rice on an area of 44.0 M ha, with a production of 116.48 million tonnes and a productivity of 2647 kg/ha (5). India will need to produce 137 million tonnes of rice by 2050 (6). Hybrid breeding is an effective strategy to solve the food shortage caused by the ever-increasing world population (7).

In this context, combining ability studies using line × tester analysis have emerged as valuable tools for evaluating the genetic potential of rice hybrids and identifying superior combinations with

enhanced yield attributes (8). Combining ability studies offer a systematic approach for exploiting genetic diversity and heterosis in rice improvement, paving the way for the high-yielding rice varieties that are capable of meeting the demands of a growing global population. By selecting parental lines with high general combining ability (GCA) and identifying cross combinations with superior specific combining ability (SCA), breeders can develop superior hybrids with improved agronomic traits and resilience to biotic and abiotic stresses. As global food demand continues to rise, investing in hybrid breeding programs offers a sustainable solution to ensure food security and meet the challenges of the 21st century (9). Heterosis is a key genetic principle in crop improvement and its successful exploitation requires an understanding of its magnitude, which largely depends on the genetic diversity among parental lines. Heterosis is particularly significant in creating hybrids that surpass the performance of the existing leading variety (10). The

present study aims to evaluate combining ability and heterosis for agronomic traits and grain yield, with the objective of developing improved, high-yielding varieties.

Materials and Methods

Plant material

The study was conducted during kharif 2021 and kharif 2022 at the Research Farm, College of Agriculture, Indira Gandhi Krishi Vishwavidyalaya (IGKV), Raipur, Chhattisgarh, India (21.25° N, 81.63° E), situated in the Chhattisgarh Plain Agro-climatic Zone at an altitude of approximately 289.6 m above mean sea level. The experimental site falls within the dry-moist sub-humid region of central India and receives an average annual rainfall of 1250–1350 mm, with the majority of precipitation occurring during the southwest monsoon period (June–September). May is generally the hottest month, whereas December is the coolest. Meteorological parameters, including temperature, rainfall and relative humidity, were recorded throughout the crop growth period and remained favourable for normal rice cultivation. The experimental material comprised three elite rice varieties, namely Rajeshwari, Mahamaya and IGKV R 1244, which were used as lines and four indigenous rice accessions, namely IC0491194, IC0496940, IC0491254 and IC0558317, which were used as testers. The tester accessions were obtained from the Coordinated Research Project (CRP) on Agrobiodiversity and were selected from indigenous collections of diverse origin and contrasting traits. All parental materials were obtained from IGKV, Raipur, Chhattisgarh, India.

Development and evaluation of F₁ hybrids

During kharif 2020, 12 F₁ hybrids were developed by crossing three lines with four testers following a line × tester mating design. For hybridisation, panicles at the appropriate flowering stage were selected and the upper and lower spikelets were removed, retaining only the middle spikelets. Emasculation was performed by carefully removing all six anthers without damaging the stigma or ovary and the emasculated panicles were immediately bagged to prevent unwanted pollination. Controlled pollination was carried out during anthesis using fresh pollen collected from the respective male parent, followed by re-bagging and proper tagging of the pollinated panicles for identification. The resulting twelve F₁ hybrids, along with their parents, were evaluated during kharif 2021 in a randomised complete block design (RCBD) with 2 replications at a spacing of 20 × 10 cm.

Phenotypic evaluation

Data were recorded for five randomly selected plants in each cross combination along with their parents in each replication for various traits, including plant height (cm), days to 50 % flowering, panicle length (cm), number of effective tillers per plant, number of tillers per plant, number of filled grains per panicle, number of unfilled grains per panicle, spikelet fertility (%), biological yield per plant (g), harvest index (%), 100 seed weight (g) and seed yield per plant (g). For heterosis estimation, negative heterosis was considered desirable for days to 50 % flowering and plant height to achieve earliness and reduced lodging susceptibility, respectively. Positive heterosis was considered desirable for grain yield and other yield-contributing traits, including panicle length, tiller number, filled grains per panicle, spikelet fertility, biological yield, harvest index and 100-seed weight.

Statistical analysis

Analysis of variance (ANOVA) for the line × tester mating design was performed to estimate GCA, SCA and associated variance components. R statistical software (version R i386 3.3.2) was used for the computation of genetic parameters, including genetic variance components and heritability estimates. Descriptive statistics such as mean, standard deviation (SD), standard error (SE) and coefficient of variation (CV) (%) were calculated using Microsoft Excel (11).

Results

Treatment variance was significant for all traits. Parent variance was significant except for effective tillers per plant. Hybrid variance was significant except for spikelet fertility. Tester variance was significant except for the number of unfilled grains per panicle. Line vs. tester variance was significant except for panicle length, effective tillers per plant and the number of unfilled grains per panicle. Parent vs. hybrid variance was significant except for panicle length, effective tillers per plant, the number of tillers per plant, the number of unfilled grains per panicle and spikelet fertility. Line variance was significant except for effective tillers per plant, the number of tillers per plant, the number of unfilled grains per panicle, spikelet fertility, biological yield per plant and seed yield per plant (Table 1). The observed significant variation among genotypes indicates the presence of substantial genetic variability for the studied traits.

The GCA effects were significant on various traits observed in two parental lines: Rajeshwari exhibited significant positive GCA effects for seed yield per plant, biological yield and 100-seed weight, whereas Mahamaya showed significant negative GCA effects for plant height and IGKV R 1244, which showed high GCA for the number of filled grains per panicle, spikelet fertility (%), seed yield per plant and harvest index. Among the testers, IC0558317 displayed significant GCA values for biological yield per plant, seed yield per plant and harvest index, while IC0491194 exhibited significant GCA effects on the number of unfilled grains per panicle, biological yield and 100-seed weight (Table 2). For plant height, two lines (Mahamaya and IGKV R 1244) and one tester (IC0496940) demonstrated significant negative GCA effects, indicating desirable reductions in plant height. Hybrids such as Rajeshwari × IC0491254 and Mahamaya × IC0496940 exhibited desirable and significantly negative SCA effects for days to 50 % flowering, while Mahamaya × IC0491254 and IGKV R 1244 × IC0496940 showed similar effects for plant height. Regarding yield traits, hybrids IGKV R 1244 × IC0558317, Rajeshwari × IC0491254 and Mahamaya × IC0491254 recorded high and significant SCA effects (Table 3). The results indicate that the trait expression is controlled by both additive and non-additive gene actions.

In days to 50 % flowering, cross Mahamaya × IC0496940 demonstrated the highest negative heterosis of -15.65 % (Table 4). For plant height, the cross IGKV R 1244 × IC0496940 exhibited negative heterosis of -8.51 %. The cross IGKV R 1244 × IC0491254 showed significant mid-parent heterosis of 14.67 % on panicle length. For both the number of effective tillers and total tillers per plant, the cross Mahamaya × IC0496940 exhibited the highest significant positive mid-parent heterosis of 53.85 and 33.33 % respectively. The cross Mahamaya × IC0496940 showed positive significant heterosis of 20.31 % for number of filled grains per panicle. For number of unfilled grains per panicle, the cross IGKV R 1244 × IC0558317 showed the highest negative heterosis of -35.25 %.

Table 1. Analysis of variance for L × T

Line × tester ANOVA													
SV	Df	1	2	3	4	5	6	7	8	9	10	11	12
Replicates	2	42.59	34.56	22.39	6.62	6.38	32.10	89.83	152.25	53.90	96.17	210.88	0.007
Treatments	18	101.57 **	634.06 **	15.92 *	9.75 *	11.88 **	2261.80 **	70.19 **	80.06 **	1184.06 **	218.35 **	189.54 **	0.52 **
Parents	6	139.98 **	965.73 **	22.50 *	7.59	11.79 **	3950.47 **	26.01	134.21 **	431.87 **	122.73 **	114.95 **	0.31 **
Parents (Line)	2	57.00 **	179.16 *	46.66 **	2.57	2.09	3740.01 **	28.09	5.41	16.01	18.32	80.61 *	0.28 **
Parents (Testers)	3	21.77 **	766.20 **	7.129	7.61	12.19 **	2053.46 **	33.02	168.10 **	450.34 **	38.33 **	53.67	0.42 **
Parents (L vs T)	1	660.57 **	3137.46 **	20.34	17.60	30.04 **	10062.45 **	0.82	290.14**	1208.18 **	584.74**	367.47 **	0.075 **
Parents vs Crosses	1	807.25 **	864.93 **	3.36	5.44	10.04	1533.85 **	2.56	70.95	7556.04 **	466.85 **	720.65 **	0.89 **
Crosses	11	16.47 **	432.16 **	13.48	11.31 *	12.09 **	1406.89 **	100.44 **	51.35	1015.08 **	247.92 **	181.94 **	0.58 **
Line effect	2	11.11	554.52	28.59 *	5.14	5.10	2992.22	92.50	115.64	1454.52	563.12	379.63	0.90
Tester effect	3	11.74	782.67	19.36	18.23	21.22	1383.05	188.16	58.67	432.17	177.14	191.00	0.89
Line × tester effect	6	20.63 **	216.11 **	5.50	9.91	9.86 **	890.36 **	59.23 *	26.26	1160.06 **	178.25 **	111.51 **	0.32 **
Error	36	4.00	34.82	7.83	4.37	2.58	85.61	20.33	26.54	10.64	5.94	24.72	0.001
Total	56	36.74	227.42	10.95	6.18	5.70	783.19	38.84	48.23	389.36	77.44	84.34	0.17

*Significant at $p = 0.05$ level, **Significant at $p = 0.01$ level; 1: days to 50 % flowering; 2: plant height (cm); 3: panicle length (cm); 4: Number of effective tillers per plant; 5: total tillers per plant; 6: number of filled grains per panicle; 7: number of unfilled grains per panicle; 8: spikelet fertility (%); 9: biological yield per plant (g); 10: seed yield per plant (g); 11: harvest index (%); 12: 100 seed weight (g).

Table 2. General combining ability effects of parents for yield and yield related traits

General combining ability												
Characters	1	2	3	4	5	6	7	8	9	10	11	12
Rajeshwari	1.11	7.83 **	1.1	0.56	0.24	-1.31	0.5	-1.46	12.37 **	5.70 **	2.126	0.315 **
Mahamaya	0.56	-4.28 *	-1.76 *	-0.71	-0.73	-15.09 **	2.48	-2.1	-8.70 **	-7.59 **	-6.38 **	-0.186 **
IGKV R 1244	0.56	-3.56 *	0.65	0.15	0.49	16.40 **	-2.99 *	3.56 *	-3.67 **	1.89 *	4.25 **	-0.130 **
IC0496940	-0.16	-5.89 **	-1.98 *	0.33	0.58	17.18 **	-3.65 *	1.75	-4.99 **	-2.12 *	0.894	-0.026 *
IC0491194	-0.05	4.67 *	1.2	-0.56	-0.98	-11.18 **	6.56 **	-3.75 *	6.27 **	-1.18	-4.77 **	0.39 **
IC0491254	-1.27	10.69 **	1.01	1.79 *	1.88 **	-6.34	-2.45	1.43	-6.92 **	-3.23 **	-2.09	-0.001
IC0558317	1.50 *	-9.48	-0.22	-1.56 *	-1.48 *	0.34	-0.456	0.56	5.63 **	6.53 **	5.97 **	-0.37 **
CD 95 % GCA (Line)	1.19	3.53	1.67	1.25	0.96	5.53	2.7	3.08	1.95	1.45	2.97	0.02
CD 95 % GCA (Tester)	1.38	4.08	1.94	1.44	1.11	6.39	3.11	3.56	2.25	1.68	3.43	0.02

*Significant at $p = 0.05$ level, **Significant at $p = 0.01$ level; GCA: general combining ability; 1: days to 50 % flowering; 2: plant height (cm); 3: panicle length (cm); 4: Number of effective tillers per plant; 5: total tillers per plant; 6: number of filled grains per panicle; 7: number of unfilled grains per panicle; 8: spikelet fertility (%); 9: biological yield per plant (g); 10: seed yield per plant (g); 11: harvest index (%); 12: 100 seed weight (g).

Table 3. Specific combining ability effects of hybrids for yield and yield related traits

Specific combining ability												
Cross	1	2	3	4	5	6	7	8	9	10	11	12
Rajeshwari × IC0496940	2.00	-0.44	0.28	-0.21	-0.38	13.31 *	-2.46	-0.98	-11.71 **	-0.65	4.79	-0.11 **
Rajeshwari × IC0491194	0.22	3.25	-1.38	-1.66	-1.36	-4.98	-3.08	2.11	-0.72	-2.72	-3.33	-0.06 **
Rajeshwari × IC0491254	-3.22 *	1.51	0.33	2.86 *	2.98 **	-16.6 **	1.80	-1.68	17.97 **	7.07 **	1.05	0.39 **
Rajeshwari × IC0558317	1.00	-4.32	0.76	-0.99	-1.24	8.28	3.74	0.55	-5.53 **	-3.69 *	-2.52	-0.23 **
Mahamaya × IC0496940	-3.33 **	9.96 **	0.56	0.27	-0.06	-13.9 *	-2.44	2.16	17.09 **	1.28	-8.75 **	0.36 **
Mahamaya × IC0491194	-0.11	1.09	1.72	0.43	0.49	8.54	3.27	-1.54	5.34 **	2.59	0.10	-0.02
Mahamaya × IC0491254	3.44 **	-9.48 *	-1.49	-1.93	-0.84	22.89 **	-2.78	3.09	-1.14	3.10 *	5.19	-0.24 **
Mahamaya × IC0558317	1.12	-1.57	-0.79	1.23	0.40	-17.46 **	1.96	-3.71	-21.2 **	-6.98 **	3.46	-0.11 **
IGKV R 124 × IC0496940	1.33	-9.52 *	-0.85	-0.06	0.43	0.66	4.91	-1.18	-5.38 **	-0.62	3.96	-0.26 **
IGKV R 124 × IC0491194	-0.11	-4.34	-0.34	1.23	0.86	-3.56	-0.18	-0.56	-4.61 *	0.13	3.23	0.081 **
IGKV R 124 × IC0491254	-0.22	7.97 *	1.16	-0.93	-2.14 *	-6.27	0.97	-1.41	-16.8 **	-10.18 **	-6.25 *	-0.16 **
IGKV R 124 × IC0558317	-1.01	5.89	0.03	-0.24	0.84	9.17	-5.69 *	3.15	26.82 **	10.68 **	-0.94	0.34 **
CD 95 % SCA	2.39	7.06	3.35	2.50	1.93	11.08	5.39	6.16	3.90	2.92	5.95	0.04

*Significant at $p = 0.05$ level, **Significant at $p = 0.01$ level; SCA: specific combining ability; 1: days to 50 % flowering; 2: plant height (cm); 3: panicle length (cm); 4: Number of effective tillers per plant; 5: total tillers per plant; 6: number of filled grains per panicle; 7: number of unfilled grains per panicle; 8: spikelet fertility (%); 9: biological yield per plant (g); 10: seed yield per plant (g); 11: harvest index (%); 12: 100 seed weight (g).

Table 4. Estimation of mid parent heterosis for yield and yield attributing traits in rice (%)

Cross	1		2		3		4		5		6	
	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP
Rajeshwari × IC0496940	-4.27*	-1.82*	11.36*	31.06*	-4.93*	-12.32*	7.32*	-12*	17.07**	-11.11*	10.77*	-8.62*
Rajeshwari × IC0491194	-2.76*	2.32*	29.73*	44.39*	7.24*	4.76*	7.14*	-2.91*	3.23*	-11.16*	-0.27*	-12.35*
Rajeshwari × IC0491254	-11.50*	-9.42*	19.86*	54.66*	2.95*	4.48*	46.94**	-2.68*	31.03**	-13.63*	-1.14*	-26.58*
Rajeshwari × IC0558317	-1.81*	1.11*	14.44*	25.58*	3.52*	2.08*	-30*	-39.11*	-34.78*	-42.32*	3.26*	0.23*
Mahamaya × IC0491254	-7.83*	-0.38*	3.80*	12.28*	-1.85*	-9.71*	-16.28*	-10.04*	2.22*	2.60*	1.92*	-12.91*
Mahamaya × IC0558317	-9.31*	-1.13*	-0.23*	0.099*	-16.6*	-19.71*	-27.66*	-34.6*	-30.61*	-37.00*	-20.1*	-24.65*
Mahamaya × IC0496940	-15.65*	-11.74*	11.66*	17.74*	-13.88*	-15.49*	53.85**	25.14**	33.33**	22.16**	20.31**	7.24*
Mahamaya × IC0491194	-11.19*	-4.44*	6.21*	19.14*	11.33*	5.01*	-2.7*	-14.28*	-17.39*	-29.66*	-10.46*	-10.9*
IGKV R 1244 × IC0496940	-9.66*	-2.23*	-8.51*	-0.95*	4.65*	-1.99*	13.51**	4.95*	14.89**	12.5*	12.57**	-9.96*
IGKV R 1244 × IC0491194	-7.69*	2.38*	3.29*	8.25*	2.42*	1.93*	-2.13*	-14.77*	-5.88*	-17.26*	-5.65*	-19.01*
IGKV R 1244 × IC0491254	-11.65*	-2.68*	16.41*	27.00*	14.67*	13.54*	39.39**	27.83**	17.95**	4.63*	5.11**	4.1*
IGKV R 1244 × IC0558317	-12.31*	-5.79*	8.11*	9.63*	3.71*	-3.28*	-21.05*	-31.78*	-10.2*	-24.19*	15.38**	14.97**

1: days to 50 % flowering; 2: plant height (cm); 3: panicle length (cm); 4: number of effective tillers per plant; 5: total tillers per plant; 6: number of filled grains per panicle; *Significant at $p = 0.05$ level, **Significant at $p = 0.01$ level.

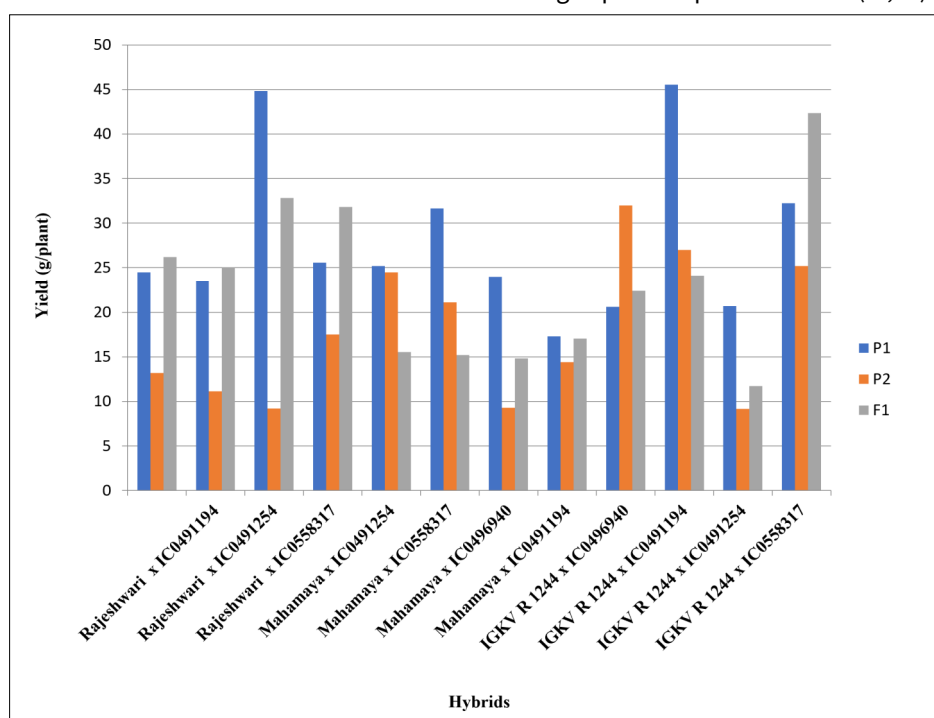
Crosses such as Mahamaya × IC0496940 (7.37 %), IGKV R 1244 × IC0558317 (6.29 %) and Rajeshwari × IC0496940 (5.42 %) showed positive mid-parent heterosis for spikelet fertility. The cross IGKV R 1244 × IC0558317 showed significant positive heterosis of 16.81 % for harvest index. The cross Rajeshwari × IC0491194 exhibited the highest positive mid-parent heterosis of 132.48 % for biological yield, followed by Mahamaya × IC0496940 (87.26 %) and Rajeshwari × IC0491254 (69.12 %). For grain yield, crosses such as IGKV R 1244 × IC0558317 (47.46 %), Rajeshwari × IC0558317 (47.66 %), Rajeshwari × IC0496940 (39.08 %) and Rajeshwari × IC0491194 (44.72 %) displayed mid-parent heterosis (Fig. 1). Positive significant heterosis for 100-seed weight was shown by cross Rajeshwari × IC0491254 (38.72 %) followed by IGKV R 1244 × IC0491194 (25.71 %).

Discussion

The significant treatment variance observed across nearly all traits indicates the presence of adequate genetic diversity among the experimental materials, providing a sound basis for further combining ability and heterosis analyses. The differential significance patterns across sources of variation, parents, hybrids, lines and testers, suggest that both additive and non-additive

genetic components are actively contributing to trait expression in this rice germplasm.

The identification of GCA and SCA effects is central to any line × tester analysis, as GCA reflects the additive genetic worth of a parent, while SCA captures non-additive interactions arising in specific hybrid combinations (12, 13). The significant positive GCA effects of Rajeshwari for seed yield, biological yield and 100-seed weight identifies it as a valuable parent for population improvement programs where selection-based approaches are intended. Similarly, IGKV R 1244 exhibited high GCA effects for filled grains per panicle, spikelet fertility, seed yield and harvest index reinforces its utility as a broadly adapted, high-yielding line. Among testers, IC0558317's significant GCA for biological yield, seed yield and harvest index suggests it possesses a strong additive genetic background for productivity-related traits. The strong GCA effects observed in this tester make it valuable for efficiently discriminating among parental lines and identifying superior hybrid combinations for breeding programmes. The significant negative GCA effects for plant height in Mahamaya, IGKV R 1244 and IC0496940 are agronomically desirable, as shorter stature is associated with reduced lodging and improved harvest index, consistent with findings reported in previous studies (14, 15).

**Fig. 1.** Bar graph showing the grain yield per plant of the F₁ hybrids with their parents.

The significant SCA effects observed in several hybrid combinations suggest that non-additive gene action, dominance and epistasis play an equally important role in governing trait expression. The negative SCA effects for days to 50 % flowering in Rajeshwari $\times$ IC0491254 and Mahamaya $\times$ IC0496940 are particularly noteworthy, as earlier flowering is a key breeding objective for short-duration rice varieties suited to multiple cropping systems. The negative SCA effects for plant height in Mahamaya $\times$ IC0491254 and IGKV R 1244 $\times$ IC0496940 further complement the GCA trends, indicating that these combinations can produce semi-dwarf, high-performing hybrids. The high positive SCA effects for seed yield per plant, biological yield, harvest index and number of filled grains per panicle in IGKV R 1244 $\times$ IC0558317, Rajeshwari $\times$ IC0491254 and Mahamaya $\times$ IC0491254 highlight these combinations as promising hybrids for advancement to multi-location evaluation. The concurrent presence of significant GCA and SCA effects across traits confirms that both selection-based and hybrid breeding strategies can be effectively deployed with this germplasm, as improvement can be pursued through additive effects via recurrent selection and through non-additive effects via targeted hybrid development.

Heterosis analysis revealed several promising hybrid combinations. Mahamaya $\times$ IC0496940 recorded significant negative mid-parent heterosis for days to 50 % flowering (-15.65 %), indicating earliness, a desirable trait for intensive cropping systems and climate resilience (16). Similarly, IGKV R 1244 $\times$ IC0496940 showed negative heterosis for plant height (-8.51 %), contributing to a compact plant type with improved lodging resistance and harvestability (17). For yield-contributing traits, IGKV R 1244 $\times$ IC0491254 exhibited positive significant heterosis for panicle length (14.67 %) (18), while Mahamaya $\times$ IC0496940 showed remarkable heterosis for effective tillers (53.85 %) and total tillers (33.33 %) (19, 20) filled grains per panicle (20.31 %) (21) and spikelet fertility (7.37 %), key traits indicating strong yield potential stable grain production under fluctuating environmental conditions (22, 23). The highly negative heterosis for unfilled grains per panicle (-35.25 %) in IGKV R 1244 $\times$ IC0558317 is a particularly valuable finding, as a reduction in sterile spikelets directly improves both grain quality and effective yield (24) and this cross also exhibited the highest positive heterosis for harvest index (16.81 %), indicating superior biomass partitioning efficiency toward grain filling a trait of paramount importance for developing high-yielding, resource-efficient varieties (25). Exceptional positive heterosis for biological yield was observed in Rajeshwari $\times$ IC0491194 (132.48 %), Mahamaya $\times$ IC0496940 (87.26 %) and Rajeshwari $\times$ IC0491254 (69.12 %), suggesting enhanced plant vigor and biomass production (26). The substantial positive mid-parent heterosis for grain yield was recorded in IGKV R 1244 $\times$ IC0558317 (47.46 %), Rajeshwari $\times$ IC0558317 (47.66 %), Rajeshwari $\times$ IC0491194 (44.72 %) and Rajeshwari $\times$ IC0496940 (39.08 %) which underscores the commercial hybrid potential of these combinations. Positive heterosis for 100-seed weight was observed in Rajeshwari $\times$ IC0491254 (38.72 %) and IGKV R 1244 $\times$ IC0491194 (25.71 %), highlighting their potential for enhanced productivity and grain quality (27).

Collectively, these findings underscore the effectiveness of utilising genetically diverse parental lines, particularly Rajeshwari, Mahamaya and IGKV R 1244, in combination with selected testers to develop promising hybrids. The identification of crosses combining desirable GCA, SCA and heterosis effects provides a strong foundation for advancing hybrid rice breeding programs targeting earliness, plant architecture and yield improvement (28).

Conclusion

The present study revealed substantial genetic variability among the parental lines and hybrids for yield and yield-related traits in rice. Both additive and non-additive gene effects contributed to trait expression, indicating the importance of integrating selection-based approaches with hybrid breeding strategies. Rajeshwari and IGKV R 1244 emerged as superior general combiners for yield and yield-attributing traits, while several hybrid combinations exhibited desirable specific combining ability and heterotic performance. Among them, IGKV R 1244 $\times$ IC0558317 and Rajeshwari $\times$ IC0496940 were identified as promising hybrids for enhancing rice productivity. These findings provide valuable insights for the development of high-yielding rice hybrids and the efficient utilisation of parental lines in future breeding programmes.

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Authors' contributions

DS conducted the research, performed data acquisition, carried out data and statistical analysis, drafted the manuscript. DG conceptualised the study, designed the research methodology and provided overall supervision of the project. SR handled the review and editing of the manuscript, VV performed the data analysis, GN performed the data curation. FTMB, JR, PKN, KS, PG, NG, VSA and SS performed data curation, review and editing of the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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