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Research Article

Estimation of combining ability and heterosis for yield and its component traits for identification of promising red rice (*Oryza sativa* L.) hybrids developed from new WA-based CMS lines and red kernel breeding lines

V. Nagamani[1], N. Shivakumar[2] and T. E. Nagaraja[3*]

[1]Department of Genetics and Plant Breeding, University of Agricultural Sciences, GKVK, Bengaluru-560065
[2]Zonal Agricultural Research Station, V.C. Farm, Mandya- 571405, UAS, GKVK, Bangalore
[3]ICAR-AICRP (Small Millets), ZARS, GKVK Campus, Bengaluru-560065.
***E-Mail:** tenagaraja@rediffmail.com

Abstract
Combining ability analysis and heterosis enables plant breeders in anticipating improvement in productivity through hybridization and selection. In this study, line × tester mating design was used to develop 42 red rice hybrids by utilizing newly developed six WA-based CMS lines and seven testers selected from red kernel breeding lines at Zonal Agricultural Research Station, V.C. Farm, Mandya during *kharif,* 2018. The phenotypic performance of hybrids along with parents and checks were evaluated for grain yield and yield contributing traits. Analysis of variance revealed that variance due to the line × tester was significant for almost all the characters studied. Combining ability analysis revealed the predominance of non-additive gene action for most of the characters studied. On the basis of *gca* effects, CMS 2 among the lines and MO-21 among testers were identified as good general combiners for most of the traits studied. High *sca* effects were observed in the crosses, *viz.,* CMS-1 × ME-19, CMS-2 × IET-14757 and CMS-4 × MSN-98 and they were also found to be the best combinations for grain yield and its component traits. The crosses CMS 5 × MSN-10-3, CMS 2 × ME-19 and CMS 5 × IET-14757 exhibited high mean grain yield and high standard heterosis over the standard commercial check KRH-4. These hybrids further need to be evaluated in multi-location trails for commercial exploitation of heterosis in red rice hybrid breeding program.

Keywords: Hybrid rice, CMS, Combining ability, Heterosis, GCA, SCA

INTRODUCTION

Rice (*Oryza sativa* L; 2n=24; estimated genome size = 430Mb) is most important food crop of the world where more than 90% of the world's rice is grown and consumed in Asia alone. In India, rice is grown in an area of 43.77 million hectares with the production and productivity levels of 111.75 million tonnes and 2.57 tonnes per hectare, respectively. In Karnataka, rice is grown in an area of 0.93 million hectares with the production and productivity levels of 2.6 million tonnes and 2.36 tonnes per hectare, respectively (*Indiastat*, 2019-20).

Red rice is a traditional pigmented rice grown in Southeast Asia and is considered highly nutritive and medicinal as it possesses antioxidant properties and also has a higher content of important micronutrients (Desai, 2012). It is an indispensable part of the festivals and rituals in India since time immemorial (Ahuja *et al*., 2008). Iron and zinc content of red rice is two to three times higher than that of white rice (Ramaiah and Rao, 1953). It has more Vitamin B_1, Vitamin B_2, Vitamin C, N, P, S, K, Mg, Ca and edible cellulose than white rice (Jing *et al*., 2000). Since red rice has many significant benefits on the human health not only in terms of food but also exhibit wide range of peculiarities such as tolerance to drought, flood, pest, diseases, salinity and alkalinity and potential to yield well even under minimum management practices.

In past few decades, the introduction of high-yielding varieties with advent of green revolution and the market demand of white rice have resulted in a drastic reduction of the area under red rice in India. However, scientists in the states of Kerala and Tamil Nadu tried to improve the grain yield and quality of red rice and a number of red rice varieties have been developed and released. But so far there are no commercial red rice hybrids are available in India. Thus, heterosis breeding is used to develop high yielding red rice hybrids with good nutritive quality that would benefit the farming community and also provides health benefits. Heterosis breeding requires the estimation of combining ability that helps in selecting desirable parents for development of superior hybrids. In this context, an effort has been made to identify restores among red kernel breeding lines and effect crosses with available new CMS lines to produce potential red rice hybrids with good grain quality.

MATERIALS AND METHODS

The experimental material for this study comprised of six newly developed CMS lines having WA type of cytoplasm and seven testers (**Table 1**) by validating SSR markers tightly linked to fertility restoration. These were crossed in line × tester mating fashion during *kharif* 2018 to produce 42 F_1 hybrids by adopting clipping and dusting method of crossing. During summer 2019, the resulted F_1 hybrids were evaluated along with their parents and four checks *viz.,* KRH-4, INDAM-300-02, Jyothi and MSN 99 in RCBD with two replications at Zonal Agricultural Research Station, V. C. Farm, Mandya. The hybrids, their parents and checks were transplanted at one seedling per hill with a spacing of 15 cm × 15 cm. All the recommended package of practices were timely followed to ensure good crop growth and development. Five competitive plants were randomly selected to record the observations on grain yield and its contributing characters *viz.,* days to 50% flowering, pollen fertility (%), plant height (cm), number of productive tillers per plant, panicle length (cm), number of spikelets per panicle, spikelet fertility (%), 1000-grain weight (g) and grain yield per plant (g). The mean values of these five plants were used for estimation of combining ability analysis (line × tester) as suggested by Kempthorne (1957). The variances for general combining ability (*gca*) and specific combining ability (*sca*) were tested against their respective error variances derived from ANOVA reduced to mean level. Significance test for *gca* and *sca* effects were performed using t-test. The per cent increase or decrease of F_1 hybrids over mid parent and standard check was calculated to estimate heterotic effects of yield and its related traits. The overall *gca* of parents was calculated based on the methods of Arunachalam and Bandyopadyay (1979) with slight modification as suggested by Mohan Rao (2001).

RESULTS AND DISCUSSION

Analysis of variance carried out for nine quantitative traits revealed presence of significant difference among the genotypes studied which indicates they are suitable for genetic studies (**Table 2**). The mean sum of squares due to parents was highly significant for all the traits except pollen fertility justifying there is a scope for selection of parents in the present material. The mean sum of squares due to crosses was also found significant for all the traits, indicating the diverse performance of different cross combinations. The variance due to parent vs. hybrids was also found highly significant for all traits revealing the presence of substantial amount of heterosis. The mean squares due to lines were significant for most of the traits studied except pollen fertility, plant height and number of productive tillers per plant. Similarly mean squares due to testers were significant for most of the traits studied except pollen fertility. Mean sum of squares due to lines × testers interaction was highly significant for all the traits indicating that the lines differed significantly from testers for all traits.

The analysis of variance for combining ability revealed that the estimates of SCA variances were predominant for all the characters except panicle length studied as evident by the ratio of GCA and SCA variances (**Table 2**). This indicates predominance of non-additive gene action in respect of all the traits studied and a very good prospect for exploitation of heterosis for improvement

Table 1. List of CMS lines and testers used in the study

S. No	Code	CMS lines	S. No	Code	Testers
1	CMS 1	KCMS 57 A	1	Tester 1	ME-19
2	CMS 2	KCMS 59 A	2	Tester 2	NSN-1-298
3	CMS 3	KCMS 54A	3	Tester 3	MSN-10-3
4	CMS 4	KCMS 29A / MSN -78A	4	Tester 4	MUKTHI
5	CMS 5	KCMS 55A	5	Tester 5	MO-21
6	CMS 6	KCMS 63A	6	Tester 6	IET-14757
			7	Tester 7	MSN-98

Table 2. Analysis of variance of combining ability for grain yield and its component traits in red rice

Source of variation	DF	Days to 50% flowering	Pollen fertility	Plant height	Number of productive tillers per plant	Panicle length	Number of spikelets per panicle	Spikelet fertility	1000-grain weight	Grain yield per plant
Replications	1	270.39**	17.480	2.82	2.401	1.008	1588.93**	270.39**	24.49**	0.013
Genotypes	54	721.65**	898.12**	163.76**	11.08**	7.462**	5642.62**	721.65**	49.00**	74.06**
Parents	12	289.55**	23.78	357.38**	5.08*	9.914**	8577.15**	289.55**	69.74**	26.08**
Parents (Line)	5	551.08**	28.09	10.90	2.66	5.680**	1932.94**	551.08**	134.97**	42.08**
Parents (Testers)	6	19.05**	23.15	443.04**	6.24*	14.850*	12328.30**	19.05**	24.66**	12.00**
Parents (lines vs. testers)	1	604.89**	6.34	1575.84**	10.193*	1.463	19291.20**	604.89**	14.09**	30.58**
Parent vs. Crosses	1	5556.11**	9906.54**	74.19*	11.07*	8.062*	1645.47**	5556.11**	4.46**	781.35**
Crosses	41	730.19**	934.31**	109.27**	12.84**	6.730**	4881.23**	730.19**	44.02**	70.86**
Line effect	5	491.75**	621.87	141.06	14.56	14.614**	7040.92	491.75	70.18	52.76**
Tester effect	6	1958.09**	1869.77**	288.28**	34.44**	17.909**	5395.69	1958.09**	27.13	121.49
Line x Tester effect	30	524.36**	799.29	68.18**	8.23**	3.181**	4418.38**	524.36**	43.04**	63.76**
Error	54	0.317	88.68	10.62	2.15	1.403	2.47	0.32	0.02	0.20
Total	109	360.150	489.04	86.42	6.58	4.401	2811.23	360.15	24.51	36.79
Variance GCA		20.11	87.53	15.87	1.72	1.158	478.167	94.20	3.74	6.69
Variance SCA		53.73	345.67	29.89	3.05	0.985	2208.124	262.02	21.51	31.835
Variance GCA/SCA		0.37	0.25	0.53	0.56	1.18	0.22	0.36	0.174	0.21

*Significant at P=0.05 level
**Significant at P=0.01 level

of these traits. These results are in accordance with the earlier findings of Mallikarjuna (2011), Khute *et al.* (2015), Savita *et al.* (2015), Kemparaju *et al.* (2018), Barhate *et al.* (2021), Hussein (2021) and Ray *et al.* (2021).

Analysis of general combining ability effects of lines and testers revealed that none of individual parent showed significant *gca* effects simultaneously in the desired direction for all the traits studied (**Table 3**). Negative *gca* effects was desirable for days to 50% flowering associated with earliness and plant height while in other traits, positive *gca* effects are considered desirable. Among the CMS lines studied, CMS 2 and CMS 5 were the best general combiners as they possessed highly significant *gca* effects for almost all the traits in desirable (positive) direction except for days to 50% flowering and pollen fertility. Among the testers, MO-21, MSN-10-3 and ME-19 were found superior general combiners for spikelet fertility, plant height, number of spikelets per panicle and grain yield per plant. For panicle length, ME-19 was found to be superior. The testers, MSN-10-3 and MO-21 were found good general combiners for spikelet fertility. While, MO-21 and MSN-98 were found good general combiners for number of spikelets per panicle. It was evident from the results that the lines CMS 2, CMS 5 and CMS 3 had high overall *gca* status. Similarly, among the seven testers studied, MO-21, MSN-10-3, ME-19 and MSN-98 possess high overall *gca* status. Similar results were reported by Abhinav and Motiramani (2006), Saidaiah *et al.* (2010) and Patil *et al.* (2011) in rice. In the present study, estimation of *gca* effects revealed the good general combiners among lines and testers for grain yield and its component traits. Hence, these good general combiners can be used as parents for red rice hybrid breeding program in the future.

The *sca* effects reflects the dominance and epistasis type of gene action and can be used as an index to determine the usefulness of a particular cross combination in the development of hybrids. The estimate of *sca* effects with their respective standard error for each character in 42 cross combinations is presented in **Table 4**. Based on the estimates of *sca* effects, none of the cross combinations exhibited significant and desirable *sca* effect for all the parameters simultaneously indicating that no specific combination was desirable for all traits. Similar observation has been reported by Tiwari *et al.* (2011) and Dwivedi and Pandey (2012) while studying the nature and magnitude of heterosis and combining ability in hybrid rice. However, majority of the crosses in the study showed significant *sca* effects, which involved at least one parent having high *gca* effects. Only 16 out of 42 crosses showed significant positive *sca* effects for grain yield per plant of which

Table 3. Estimates of general combining ability effects in lines and testers for grain yield and yield contributing characters in red rice

Parent/ Character	Days to 50% flowering	Pollen fertility	Plant height	Number of productive tillers per plant	Panicle length	Number of spikelets per panicle	Spikelet fertility	1000-grain weight	Grain yield per plant
Lines									
CMS 1	10.381**	-4.167	0.915	1.678**	0.550	-14.955**	-9.603**	-2.184**	0.269**
CMS 2	-3.333**	-2.637	2.185**	0.094	1.107**	24.538**	4.978**	-2.187**	1.689**
CMS 3	-4.405**	10.515**	-3.327**	-0.455	-1.395**	-29.223**	4.579**	-0.675**	-1.327**
CMS 4	-2.405**	-6.763*	-2.179**	-0.726	-0.804**	7.352**	0.553**	3.063**	-1.848**
CMS 5	-1.048	-2.765	4.813**	0.562	0.961**	24.923**	-4.567**	2.353**	2.845**
CMS 6	0.810	5.817*	-2.406**	-1.153**	-0.419	-12.63**	4.060**	-0.370**	-1.627**
SEm±	5.608	0.306	0.594	1.563	0.788	1.116	0.075	0.789	0.158
Testers									
Tester 1	5.464**	-10.788**	2.180*	0.771	2.549**	4.596**	4.629**	-1.465**	0.732**
Tester 2	-3.619**	-11.345**	-5.972**	-0.380	-0.151	-8.616**	-6.651**	0.951**	-3.226**
Tester 3	1.798**	12.757**	3.460**	-0.309	-0.553	-9.645**	19.276**	2.160**	5.749**
Tester 4	-1.369*	-1.343	1.866*	0.481	-0.838*	-8.019**	1.010**	-1.678**	-1.631**
Tester 5	2.048**	12.837**	3.412**	0.337	-0.127	19.748**	8.654**	-0.274**	2.134**
Tester 6	-2.286**	-14.443**	-8.147**	2.345**	-1.155**	-31.073**	-6.260**	-1.054**	-2.991**
Tester 7	-2.036**	12.325**	3.200**	-3.246**	0.275	33.010**	-20.657**	1.360**	-0.767**
SEm±	6.057	0.330	0.641	1.688	0.851	1.205	0.081	0.852	0.170

*Significant at P=0.05 level; **Significant at P=0.01 level

highest being CMS 2 × ME-19. This hybrid also had highly significant s*ca* effects for different quantitative traits such as pollen fertility, plant height, number of spikelets per panicle and spikelet fertility in positive direction.

Another hybrid combination, CMS 1 × MSN-98 was found superior for earliness as it exhibited lowest negative SCA effect for days to 50% flowering. Furthermore, the hybrid combination CMS 4 × MSN-98 was found good specific combiner for number of spikelets per panicle, panicle length, 1000-grain weight and grain yield per plant. These results are in corroboration with the earlier findings of Jagadeesan and Ganesan (2006) and Saidaiah *et al*. (2010). Twenty-two out of 42 hybrids exhibited high overall *sca* effect and 20 crosses exhibited low overall *sca* effect. All the 20 crosses with high overall *sca* effects have parents with all types of combination of *gca* effect *viz.,* H x H, H x L and L x L. The crosses CMS-1 × ME-19, CMS-2 × IET-14757 and CMS-4 × MSN-98 were identified as most promising for grain yield based on specific combination. Hence, these could be used for the exploitation of heterosis for grain yield and related characters. Damodar *et al.* (2014) and Sharma and Pandey (2021) identified good specific combiners for different yield attributing traits in rice based on high *sca* effects in desirable direction.

Identification of potential restorers from the existing red rice germplasm is required to extract unexploited heterosis in red rice hybrid breeding. The relative magnitude of heterosis was expressed as heterosis over mid parent (relative heterosis) and standard checks (standard heterosis) for yield and its component traits. The magnitude of heterosis varied from trait to trait and cross to cross and none of the cross combination recorded significant heterosis for all the traits simultaneously as shown in the **Table 5**. This observation was in agreement with the findings of Bagheri and Jelodar (2010), Hussain and Sanghera (2012) and Latha *et al.* (2013). Significant heterosis for days to 50% flowering in negative direction over mid parent (-14.21%) and over the commercial check KRH-4 (-16.10 %) was recorded by the hybrid combination CMS 3 × NSN-1-298 (-14.21%). For plant height, the cross CMS 6 × IET-14757 showed significant mid parent heterosis (-11.31 %) and standard heterosis over the check KRH-4 (-9.38 %) followed by the hybrid CMS 3 × MSN-10-3 (-8.69 %) and over the check KRH-4 (-9.04 %) in negative direction. Similarly, Tiwari *et al.* (2011) and Patil *et al.* (2012) noticed significant negative heterosis for earliness and plant height in the same crop. With respect to number of productive tillers per plant, the cross CMS 1 × IET-14757 recorded maximum heterosis over mid parent (51.52 %) and standard heterosis over commercial check KRH-4 (71.89%). Maximum relative heterosis (18.55 %) and standard heterosis (24.78 %) for panicle length was exhibited by the cross CMS 1× ME-19 followed by the other hybrid combination CMS 5× NSN-1-298 with 17.65 per cent and 17.80 per cent, respectively. Sen and Singh (2011) and Madhuri *et al*. (2017) documented similar results in their respective studies.

Table 4. Estimates of specific combining ability effects in crosses for grain yield and yield contributing characters in red rice

Cross combinations	Days to 50% flowering	Pollen fertility	Plant height	Number of productive tillers per plant	Panicle length	Number of spikelets per panicle	Spikelet fertility	1000-grain weight	Grain yield per plant
CMS 1 × Tester 1	-7.96**	18.16*	-0.17	2.34*	1.18	12.45**	11.46**	0.75**	3.89**
CMS 1 × Tester 2	-8.88**	11.03	2.30	0.325	0.38*	4.55**	28.03**	0.99**	1.09**
CMS 1 × Tester 3	12.70**	4.77	-1.54	-2.18*	1.59	35.55**	14.06**	-2.67**	3.71**
CMS 1 × Tester 4	14.37**	-28.82**	-4.36*	-0.77	-1.13	17.49**	13.58**	3.41**	4.55**
CMS 1 × Tester 5	-9.55**	17.86*	-3.00	-0.39	-1.24	15.42**	-15.82**	2.96***	-3.31**
CMS 1 × Tester 6	11.78**	-14.49	8.22**	3.52**	-0.15	-29.46**	-38.81**	1.14**	-3.95**
CMS 1 × Tester 7	-12.46**	-8.50	-1.46	-2.84**	-0.63	-55.99**	-12.49**	-6.59**	-5.98**
CMS 2 × Tester 1	0.75	32.93**	7.79**	1.17	0.43	103.51**	5.85**	-2.47**	11.00**
CMS 2 × Tester 2	1.83	-3.03	1.41	-0.97	-0.67	15.54**	-4.25**	2.28**	-0.11
CMS 2 × Tester 3	-2.58	-6.67	-2.62	3.04**	0.53**	-8.62**	-3.88**	-1.12**	-5.33**
CMS 2 × Tester 4	-2.42	14.51	-2.83	1.55	2.11	-26.58**	11.50**	3.17**	2.45**
CMS 2 × Tester 5	5.17**	-26.11**	0.03	-2.19*	-0.79	-30.04**	12.38**	2.26**	-1.82**
CMS 2 × Tester 6	-5.00**	-19.04*	-0.48	-2.01	-0.21	-67.36**	0.22	-3.23**	-4.29**
CMS 2 × Tester 7	2.25	7.38	-3.31	-0.59	-1.39	13.55**	-21.84**	-0.89**	-1.89**
CMS 3 × Tester 1	-5.18**	6.98	-0.53	-0.98	0.03	-23.77**	0.01	-0.14	-3.78**
CMS 3 × Tester 2	-0.09	6.022	-3.98	-0.48	-0.57	23.79**	8.49**	-7.12**	-0.50*
CMS 3 × Tester 3	-2.51	-2.405	-5.61**	-1.65	0.43	-20.29**	-11.94***	1.62**	5.57**
CMS 3 × Tester 4	-3.35*	7.689	-1.12	2.76*	-1.09	-44.02**	-6.46***	0.65**	-0.96**
CMS 3 × Tester 5	7.24**	-1.420	7.29**	2.31*	-0.03*	17.04**	2.22**	0.64**	-0.54*
CMS 3 × Tester 6	-1.93	-0.141	1.57	-1.00	1.58	27.73**	-2.09**	4.25**	-1.87**
CMS 3 × Tester 7	5.82**	-16.73*	2.37	-0.96	-0.35	19.514**	9.75**	0.10	2.08**
CMS 4 × Tester 1	-4.68**	-53.21**	-0.88	-0.86	-0.93	-49.89**	-12.25**	0.06	-4.14**
CMS 4 × Tester 2	5.91**	-25.44**	3.08	-0.11	-0.46*	-23.93**	-22.79**	7.30**	-1.57**
CMS 4 × Tester 3	-0.51	14.76	0.24	0.52	-1.67	-65.73**	-2.59**	-0.13	-6.62**
CMS 4 × Tester 4	-1.35	23.89**	-4.71*	-0.84	0.32	54.24**	1.159**	-9.16**	1.38**
CMS 4 × Tester 5	-1.26	1.95	-4.23*	-0.02	0.81	-10.97**	10.09**	-7.09**	1.46**
CMS 4 × Tester 6	0.07	25.55**	0.62	0.83	-0.46**	-4.16**	0.88*	2.21**	0.82**
CMS 4 × Tester 7	1.82	12.50	5.89**	0.48	2.39*	100.44**	25.51**	6.76**	8.66**
CMS 5 × Tester 1	-2.04	1.32	-8.67**	-1.65	-1.73*	-64.27**	-2.04**	3.39**	-3.92**
CMS 5 × Tester 2	3.55	6.93	3.58	1.41	1.87	10.28**	5.77**	-5.36**	1.44**
CMS 5 × Tester 3	0.63	-9.08	6.31**	2.02	-1.52	49.25**	4.57**	7.17**	9.56**
CMS 5 × Tester 4	-3.20	-33.96**	10.94**	-2.56*	1.13	14.26**	-4.82**	1.24**	-6.83**
CMS 5 × Tester 5	-1.62	14.48	-9.30**	-0.11	0.85	8.80**	-18.02**	1.46**	-2.40**
CMS 5 × Tester 6	-1.29	9.00	1.49	1.36	0.33	55.15**	25.52**	-1.63**	10.33**
CMS 5 × Tester 7	3.97	11.31	-4.35*	-0.48	-0.93	-73.47**	-10.98**	-6.29**	-8.19**
CMS 6 × Tester 1	19.11	-6.18	2.45	-0.03	1.02	21.98**	-3.03**	-1.60**	-3.06**
CMS 6 × Tester 2	-2.31	4.49	-6.39**	-0.18	-0.55	-30.23**	-15.25**	1.89**	-0.36
CMS 6 × Tester 3	-7.73	-1.42	3.22	-1.75	0.65	9.83**	-0.22	-4.88**	-6.88**
CMS 6 × Tester 4	-4.06	16.69*	2.07	-0.14	-1.35	-15.40**	-14.97**	0.68**	-0.59**
CMS 6 × Tester 5	0.02	-6.75	9.22**	0.40	0.41	-0.25	9.15**	-0.27**	6.62**
CMS 6 × Tester 6	-3.64	-0.87	-11.42**	-2.71*	-1.09	18.11**	14.28**	-2.74**	-1.02**
CMS 6 × Tester 7	-1.39	-5.96	0.87	4.40**	0.92	-4.04**	10.04**	6.91**	5.29**
C.D. @ 5%	2.95	14.84	4.14	2.08	1.57	2.09	0.81	0.19	0.42

*Significant at P=0.05 level; **Significant at P=0.01 level

Table 5. Percentage of relative heterosis (RH) and standard heterosis (SH) for different characters in red rice hybrids

Cross combinations	Days to 50% flowering		Pollen fertility		Plant height		Number of productive tillers per plant		Panicle length	
	RH	SH over KRH-4	RH	SH over KRH-4	RH	SH over KRH-4	RH	SH over KRH-4	RH	SH over KRH-4
CMS 1 × Tester 1	0.99	-0.49	-17.00	-15.72	13.14 **	18.42 **	28.73 **	48.74 **	18.55 **	24.78 **
CMS 1 × Tester 2	-8.00 **	-10.24 **	-27.63 **	-24.27 *	7.11 *	12.08 **	27.50 *	22.14	10.94 *	9.51
CMS 1 × Tester 3	16.10 **	16.10 **	-10.47	-4.43	-1.80	18.31 **	-10.04	1.68	0.19	13.00 **
CMS 1 × Tester 4	22.40 **	14.63 **	-58.53 **	-57.47 **	-0.83	13.39 **	11.72	20.17	3.27	-0.09
CMS 1 × Tester 5	-4.43 *	-5.37 *	4.27	10.21	4.55	16.63 **	17.73	22.18	5.98	2.53
CMS 1 × Tester 6	17.22 **	11.22 **	-58.47 **	-56.10 **	13.97 **	16.26 **	51.52 **	71.89 **	4.48	2.79
CMS 1 × Tester 7	-11.55 **	-12.20 **	-23.89 *	-19.67	-4.27	18.12 **	-28.87 **	-28.57 *	2.34	6.94
CMS 2 × Tester 1	0.00	-5.37 *	-1.60	2.40	21.89 **	28.72 **	17.25	25.63 *	9.76 *	23.91 **
CMS 2 × Tester 2	-7.29 **	-13.17 **	-42.34 **	-38.21 **	6.55 *	12.50 **	12.07	-2.06	0.92	7.33
CMS 2 × Tester 3	-8.63 **	-12.20 **	-22.59 *	-15.41	-2.39	18.53 **	26.39 *	32.23 *	-7.97 *	10.82 *
CMS 2 × Tester 4	-5.43 **	-15.12 **	-12.07	-7.58	1.06	16.52 **	27.42 *	26.34 *	11.60**	16.49 **
CMS 2 × Tester 5	0.51	-4.39 *	-41.76 **	-36.98 **	7.94 **	21.43 **	-1.72	-6.26	2.40	6.89
CMS 2 × Tester 6	-10.46 **	-18.54 **	-62.54 **	-59.46 **	4.86	7.96 *	6.76	12.14	-0.97	5.00
CMS 2 × Tester 7	-6.91 **	-11.22 **	-7.75	-0.31	-5.52 *	17.47 **	-16.30	-22.98	-5.41	6.06
CMS 3 × Tester 1	-11.11 **	-12.20 **	-11.31	-11.83	9.35 **	13.28 **	-3.92	2.94	5.44	11.26 *
CMS 3 × Tester 2	-14.21 **	-16.10 **	-15.65	-13.52	-3.12	0.33	11.54	-2.52	-2.14	-3.14
CMS 3 × Tester 3	-13.38 **	-13.17 **	-0.69	3.91	-8.69 **	9.04 **	-15.66	-11.76	-12.00**	-0.52
CMS 3 × Tester 4	-11.69 **	-17.07 **	-0.99	-0.54	-0.89	12.28 **	33.05 **	31.93 *	-5.55	-8.38
CMS 3 × Tester 5	-2.70	-3.41	1.47	5.10	11.67 **	23.38 **	33.04 **	26.89 *	2.38	-0.68
CMS 3 × Tester 6	-12.31 **	-16.59 **	-26.45 **	-23.81 *	3.12	4.10	10.40	15.97	3.27	1.88
CMS 3 × Tester 7	-8.33 **	-8.78 **	-15.39	-12.49	-3.82	17.65 **	-24.66 *	-30.67 *	-4.85	-0.33
CMS 4 × Tester 1	-6.57 **	-9.76 **	-98.06 **	-97.98 **	6.98 *	14.17 **	-6.56	1.68	7.80	9.64
CMS 4 × Tester 2	-4.08 *	-8.29 **	-69.92 **	-67.71 **	2.62	9.49 **	10.38	-1.68	4.99	-0.09
CMS 4 × Tester 3	-7.46 **	-9.27 **	-5.19	3.79	-4.64 *	16.85 **	-1.98	4.20	-14.97**	-7.11
CMS 4 × Tester 4	-5.32 **	-13.17 **	-6.67	-1.74	-5.90 *	9.54 **	-1.46	-0.63	7.67	0.35
CMS 4 × Tester 5	-7.04 **	-9.76 **	-17.32	-10.37	-1.60	11.80 **	8.23	5.04	13.28 **	5.58
CMS 4 × Tester 6	-6.04 **	-12.68 **	-21.10 *	-14.46	0.23	4.31	20.98 *	29.12 *	0.75	-4.45
CMS 4 × Tester 7	-8.27 **	-10.73 **	-6.88	0.80	-2.06	22.86 **	-15.56	-20.88	13.13 **	14.20 **
CMS 5 × Tester 1	-4.22 *	-5.85 **	-35.79 **	-32.89 **	5.87 *	13.28 **	-3.08	5.88	6.75	13.87 **
CMS 5 × Tester 2	-6.77 **	-9.27 **	-32.42 **	-27.27 *	10.17 **	17.86 **	36.15 **	21.85	17.65 **	17.80 **
CMS 5 × Tester 3	-6.60 **	-6.83 **	-25.52 **	-18.28	7.00 **	31.42 **	19.57	27.61 *	-11.35**	1.24
CMS 5 × Tester 4	-7.57 **	-13.66 **	-63.63 **	-61.61 **	15.54 **	34.82 **	-5.39	-4.20	13.64 **	11.56 *
CMS 5 × Tester 5	-7.65 **	-8.78 **	-0.61	8.01	0.05	13.95 **	18.10	15.13	15.56 **	13.44 **
CMS 5 × Tester 6	-7.73 **	-12.68 **	-34.13 **	-28.41 *	8.37 **	13.09 **	34.75 **	44.37 **	6.89	6.68
CMS 5 × Tester 7	-6.40 **	-7.32 **	-4.24	3.91	-5.16 *	19.24 **	-12.95	-18.07	1.44	7.44
CMS 6 × Tester 1	18.02 **	16.59 **	-32.48 **	-31.69 **	12.22 **	17.63 **	-11.50	5.04	11.33 **	19.85 **
CMS 6 × Tester 2	-11.22 **	-13.17 **	-23.72 *	-20.45	-5.86 *	-1.34	-4.88	-5.88	0.11	1.22
CMS 6 × Tester 3	-13.38 **	-13.17 **	-6.22	-0.22	-0.60	19.92 **	-29.84 **	-18.49	-9.13 *	4.67
CMS 6 × Tester 4	-7.01 **	-12.68 **	1.99	4.25	2.05	16.85 **	-8.16	1.68	-4.47	-5.28
CMS 6 × Tester 5	-4.67 *	-5.37 *	-10.81	-6.05	13.29 **	26.56 **	-1.77	5.04	6.40	5.50
CMS 6 × Tester 6	-8.72 **	-13.17 **	-33.41 **	-29.85 *	-11.31 **	-9.38 **	-17.84	-4.20	-6.28	-5.54
CMS 6 × Tester 7	-10.29 **	-10.73 **	-10.39	-5.74	-5.30 *	17.00 **	4.79	8.53	2.41	9.47

*Significant at P=0.05 level; **Significant at P=0.01 level

Table 5. Continued

Cross combinations	Number of spikelets per panicle		Spikelet fertility		1000-grain weight		Grain yield per plant	
	RH	SH over KRH-4	RH	SH over KRH-4	RH	SH over KRH-4	RH	SH over KRH-4
CMS 1 × Tester 1	11.53 **	31.38 **	-10.65 **	-19.62 **	19.56 **	21.69 **	8.73 **	34.94 **
CMS 1 × Tester 2	-26.23 **	16.47 **	-7.53 **	-14.14 **	23.84 **	38.09 **	-31.21 **	-7.82 **
CMS 1 × Tester 3	-23.22 **	37.65 **	10.12 **	-1.73 **	16.89 **	22.98 **	28.66 **	65.51 **
CMS 1 × Tester 4	11.70 **	26.04 **	-12.27 **	-21.18 **	4.22 **	36.77 **	-16.73 **	24.11 **
CMS 1 × Tester 5	32.24 **	44.19 **	-39.20 **	-43.76 **	13.42 **	42.62 **	-27.28 **	-1.80
CMS 1 × Tester 6	-33.27 **	-23.44 **	-81.66 **	-83.09 **	10.20 **	26.65 **	-54.48 **	-38.29 **
CMS 1 × Tester 7	-31.83 **	3.10 **	-67.20 **	-70.72 **	-22.91 **	-6.09 **	-52.31 **	-37.03 **
CMS 2 × Tester 1	106.57 **	123.64 **	19.17 **	-10.32 **	-17.80 **	1.88 *	48.12 **	88.92 **
CMS 2 × Tester 2	2.56 **	52.14 **	-13.64 **	-32.50 **	9.21 **	45.97 **	-31.97 **	-6.49 **
CMS 2 × Tester 3	-20.85 **	34.34 **	27.15 **	-5.21 **	4.02 **	32.49 **	-11.19 **	17.31 **
CMS 2 × Tester 4	18.87 **	22.80 **	22.15 **	-8.20 **	-11.82 **	35.26 **	-21.44 **	19.81 **
CMS 2 × Tester 5	40.67 **	39.97 **	29.35 **	0.64	-6.50 **	38.28 **	-15.79 **	16.61 **
CMS 2 × Tester 6	-26.15 **	-22.31 **	-6.37 **	-27.45 **	-27.27 **	-0.31	-50.71 **	-31.49 **
CMS 2 × Tester 7	27.14 **	80.15 **	-53.45 **	-65.29 **	-10.41 **	28.98 **	-27.78 **	-2.15
CMS 3 × Tester 1	-7.77 **	-4.29 **	-14.16 **	-16.79 **	23.11 **	25.54 **	-33.68 **	-23.70 **
CMS 3 × Tester 2	-16.59 **	19.98 **	-19.55 **	-19.69 **	-12.78 **	-2.58 **	-42.41 **	-28.04 **
CMS 3 × Tester 3	-46.68 **	-11.89 **	-10.62 **	-13.99 **	50.49 **	58.62 **	39.80 **	67.18 **
CMS 3 × Tester 4	-26.64 **	-27.51 **	-24.88 **	-27.26 **	-1.78 **	29.08 **	-43.44 **	-20.82 **
CMS 3 × Tester 5	42.37 **	35.26 **	-9.85 **	-10.32 **	9.30 **	37.63 **	-16.15 **	5.63 **
CMS 3 × Tester 6	6.15 **	6.89 **	-29.68 **	-30.27 **	34.72 **	55.08 **	-48.77 **	-35.19 **
CMS 3 × Tester 7	6.69 **	46.37 **	-30.31 **	-32.92 **	18.34 **	44.37 **	-15.55 **	3.86 *
CMS 4 × Tester 1	21.32 **	3.10 **	-30.03 **	-33.69 **	2.00 **	49.75 **	-52.34 **	-29.34 **
CMS 4 × Tester 2	-10.35 **	12.11 **	-55.30 **	-56.34 **	33.62 **	109.17 **	-60.80 **	-38.01 **
CMS 4 × Tester 3	-44.11 **	-18.16 **	-2.69 **	-8.47 **	13.74 **	70.89 **	-43.23 **	-13.26 **
CMS 4 × Tester 4	109.68 **	67.77 **	-19.22 **	-23.53 **	-47.96 **	-8.28 **	-47.64 **	-9.30 **
CMS 4 × Tester 5	85.41 **	41.31 **	-3.75 **	-6.33 **	-33.64 **	13.32 **	-27.76 **	15.00 **
CMS 4 × Tester 6	34.54 **	10.20 **	-29.24 **	-31.37 **	3.45 **	65.48 **	-50.84 **	-21.49 **
CMS 4 × Tester 7	93.76 **	129.41 **	-15.76 **	-20.75 **	24.89 **	108.37 **	-8.95 **	42.22 **
CMS 5 × Tester 1	-0.40	5.35 **	-15.12 **	-28.41 **	4.13 **	65.88 **	-22.53 **	1.80
CMS 5 × Tester 2	1.95 **	48.70 **	-22.07 **	-32.02 **	-24.90 **	26.92 **	-21.71 **	10.63 **
CMS 5 × Tester 3	4.95 **	75.51 **	11.97 **	-6.35 **	29.94 **	111.45 **	60.99 **	118.86 **
CMS 5 × Tester 4	50.72 **	51.93 **	-22.89 **	-35.05 **	-19.81 **	51.35 **	-56.24 **	-31.58 **
CMS 5 × Tester 5	72.87 **	67.69 **	-31.90 **	-40.82 **	-11.96 **	61.32 **	-15.52 **	20.25 **
CMS 5 × Tester 6	60.19 **	64.53 **	2.68 **	-11.11 **	-20.24 **	37.54 **	17.86 **	68.39 **
CMS 5 × Tester 7	-14.56 **	18.93 **	-56.88 **	-63.92 **	-31.02 **	23.69 **	-53.06 **	-34.59 **
CMS 6 × Tester 1	26.98 **	39.76 **	-18.16 **	-20.49 **	15.43 **	18.40 **	-48.31 **	-21.08 **
CMS 6 × Tester 2	-37.71 **	-6.47 **	-44.90 **	-44.87 **	37.85 **	54.80 **	-56.36 **	-29.05 **
CMS 6 × Tester 3	-29.39 **	21.11 **	1.23 *	-2.36 **	13.73 **	20.55 **	-44.99 **	-13.51 **
CMS 6 × Tester 4	-0.64	4.43 **	-34.70 **	-36.63 **	-0.69	31.11 **	-55.18 **	-20.38 **
CMS 6 × Tester 5	33.03 **	34.76 **	-3.39 **	-3.67 **	5.86 **	33.94 **	-8.88 **	49.08 **
CMS 6 × Tester 6	4.51 **	11.82 **	-13.29 **	-13.82 **	-1.56 *	13.91 **	-58.41 **	-31.74 **
CMS 6 × Tester 7	-1.42 *	41.45 **	-30.72 **	-33.16 **	53.44 **	88.12**	-23.85 **	22.31 **

*Significant at P=0.05 level; **Significant at P=0.01 level

For spikelet fertility, cross combination CMS 3 × IET-14757 exhibited significant mid parent heterosis (29.68%). While, no single hybrid exhibited significant positive standard heterosis over the check KRH-4. The hybrid combination CMS 4 × MUKTHI recorded highest heterosis over mid parent (109.68%) and over the commercial check KRH-4 (67.77%) for number of spikelets per panicle. Faiz *et al.* (2006) reported significant positive heterosis for number of grains per panicle which in turn directly contributes to grain yield. The hybrid combination CMS 6 × MSN-98 showed highest mid parent heterosis (53.44%) and standard heterosis over the check KRH-4 (88.12%) for 1000-grain weight. Gnanasekaran (2006) reported significant heterosis for 1000-grain weight.

Grain yield is a complex trait as it is a multiplicative end product of several yield attributing components. Many hybrids showed positive significant heterosis for this trait. The range of relative heterosis recorded ranged from -60.80 (CMS 4 × NSN-1-298) to 60.99 per cent (KCMS 5 × MSN-10-3). Considering commercial check KRH-4, the crosses CMS 5 × MSN-10-3, CMS 2 × ME-19 and CMS 5 × IET-14757 exhibited higher grain yield and standard heterosis. Hence, these hybrids could be further tested in multi-location trails before go for commercial cultivation. Gokulakrishnan and Kumar (2013) reported relative heterosis from -29.32 to 65.73 per cent for grain yield while working on rice crop.

From the study, among the lines CMS 2 had significant *gca* effects in desired direction for important yield contributing traits *viz.,* panicle length, number of productive tillers per plant, spikelet fertility, number of spikelets per panicle and 1000-grain weight. Similarly, among the testers, MO-21, MSN-10-3 and ME-19 were found superior general combiners for spikelet fertility, plant height, spikelet number per panicle and grain yield per plant. The crosses CMS-1 × ME-19, CMS-2 × IET-14757 and CMS-4 × MSN-98 were identified as most promising hybrids for grain yield based on sca effect and standard heterosis over commercial check KRH-4. Hence, these promising hybrids need further testing in multi-location yield trials to exploit their heterotic potential for the development of successful red rice hybrid in the future days.

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