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Research Article

Study on combining ability and heterosis for yield and nutritional traits in rice (*Oryza sativa* L.)

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Abstract
Rice (*Oryza sativa* L.) is the staple food for more than 50% of the world's population. Micronutrient malnutrition is a significant issue affecting approximately 2 billion people globally with severe levels of hunger. Fifteen hybrids derived through 6 x 6 half diallel mating were evaluated along with the six parents in a randomized block design at Tamil Nadu Rice Research Institute, Aduthurai during *Kharif*, 2022. Analysis of variance showed significant differences among the genotypes for all the traits except for the flag leaf width. The GCA effects of CO54 and *Kalanamak* were significant for most of the quantitative traits including grain yield, indicating the usefulness of these two genotypes for improving yield contributing traits. The parents such as *Kalanamak* and *Chinkinikar* registered high mean values for Fe and Zn and therefore these two parents can be exploited to develop Fe and Zn rich high yielding varieties. Analysis of specific combining ability and heterosis *per se* of the hybrids indicated that the crosses *viz*., ADT56/*Kalanamak*, CO54/*Kalanamak* and CO54/*Chinkinikar* were best hybrids for improving yield as well as nutritional traits.

Keywords: Half diallel; hybrids; GCA and SCA; grain yield; nutritional traits

INTRODUCTION

Rice (*Oryza sativa* L.) is the most important crop for global nutrition and the primary source of energy for people in Asia, Africa, and Latin America (Fukagawa and Ziska, 2019). Worldwide, during the year 2021, more than 3% of the agriculture area (162 million ha) was used for rice cultivation and produced 755 million tonnes (FAOSTAT, 2021). Micronutrient malnutrition affects around two billion people worldwide and most countries in West Africa have serious levels of hunger (Global Hunger Index, 2019). The people living in West and Central Africa do not have access to nutritionally balanced food products. As a result, they suffer from micronutrient malnutrition or "hidden hunger" (Badu- Apraku and Fakorede, 2017). Protein content (PC), one of the most important nutritional quality indicators in rice grain, is around 8.5% but the commonly consumed milled rice contains an average of about 7% (Pradhan *et al*., 2019). Protein serves as a storage vacuole for Fe and Zn in different regions of rice plant, such as the embryo and aleurone layer. These layers account for 90% of the Fe and Zn content in rice grain. Zinc (Zn) plays a significant role in the biosynthesis and turnovers of proteins, nucleic acids, carbohydrates and lipids. Nearly one in five people is estimated to be zinc deficient, which contributes to childhood stunting as well as illness and even death in early life especially among people living in low-and middle-income countries (Black *et al*., 2013). Iron (Fe) deficiency has been identified as the major micronutrient problem which affects approximately one billion people globally and it is frequently associated with anemia (Bailey *et al*., 2015). Mostly rice is consumed as milled grains or white rice, which is either cooked directly or made into flour or batter to make various preparations (Gyani *et al*., 2020). During milling and polishing process nutrients became leached out due to the removal of the husk. This leads to malnutrition in rice dependent consumers.

Landraces may have varying levels of vitamins, minerals and other essential nutrients (Rathna Priya *et al*., 2019). In most of the landraces, protein content ranges from 6.9 to 12.4%, Fe from 7.8 mg kg^{-1} to 19 mg kg^{-1}, and Zn from 13.3 mg kg^{-1} to 32 mg kg^{-1}(Kampuang *et al*., 2017). Mahender *et al*., 2016; Mohanty *et al*., 2011, have reported protein content of 16.41% in the grains of the accession ARC10063. Bio-fortification is the process of increasing the density of micronutrients in widely-consumed staple crops through conventional breeding techniques or genetic modification so that consumption of the same can provide essential micronutrients to improve nutrition and health. By focusing on these nutritional traits in landraces, breeders can develop nutrient rich varieties which could be used to improve nutrition security. However, the traditional breeding method could only achieve limited success. According to previous studies (Cofman and Juliano, 1987; Yu *et al*., 2009), grain protein content and nutritional traits had low and negative association with grain yield. To meet the requirements of consumers, an enhanced change in the development of rice with nutritional quality is required for which classical breeding combined with a molecular method will be extremely beneficial (Wang *et al*., 2020). Consumer acceptability and awareness of nutritionally enriched foods may aid in the development of micronutrient enriched rice varieties (Khatoon and MT, 2020). So, there is high demand of development of bio-fortified rice varieties by genetic modification, genome editing and transgenic approaches that meet nutritional needs and regulatory standards which is lack in natural resources or existing varieties (Gaoh *et al*., 2023).

The use of stable hybrids rich in Fe, Zn and protein concentration coupled with high grain yield is an appropriate and sustainable strategy for resource-poor farmers to alleviate hidden hunger. Hence, the present study was undertaken to assess of grain Fe and Zn concentrations, protein percentage, grain yield, flowering time, panicle length and plant weight to determine the combining abilities, estimate the heterosis, and to identify rice hybrids for high grain Fe, Zn and protein content and high grain yield.

MATERIALS AND METHODS

The genetic material for the study comprised of six genotypes (**Table 1**) consisting of three high yielding commercial varieties and three landraces and 15 hybrids obtained by crossing the above parents in half diallel fashion (Method II; Model I). A total of 21 genotypes (six parents and fifteen hybrids were evaluated in RCBD (randomized complete block design), with three replications during *kharif*2022 at Tamil Nadu Rice Research Institute, Aduthurai. Single seedling per hill was transplanted with spacing of 30 x 20 cm. Observations were recorded on five random plants in each genotype in each replication for morphological characters *viz*., plant height (PH), number of productive tillers/plant (NPT), flag leaf length (FL), flag leaf width (FW), panicle length (PL), panicle weight (PW), filled grains/panicle (FG), unfilled grains/panicle (UFG), total number of grains/panicle (TNG), single plant yield (SPY), and length to breadth ratio of the grain (L/B). Days to 50% flowering (DFF) was recorded on plot basis. Length / breadth ratio of 10 whole milled rice were measured by using graph sheet and length/breadth ratio was computed as per Murthy and Govinda Swamy (1967). Nutritional traits like Iron (Fe) and Zinc (Zn) were analyzed by using Hitachi X- supreme ED-XRF Spectrophotometer and protein by PERTEN IM 9500 Near Infrared spectroscopy.

Statistical Analysis: The data collected were subjected to Analysis of Variance (ANOVA) (Panse and Sukhatme, 1961) using TNAUSTAT software. The combining ability analysis was carried out as per Griffing (1956), method-2 (Model-I). Combining ability of the parents were assessed based on analysis of variances of general combining ability (GCA) and specific combining ability (SCA). Based on general combining ability (*gca*) and specific combining ability (*sca*) effects gene action for each trait was worked out. Mid-parent heterosis, better-parent heterosis and standard heterosis were calculated as per Fonseca and Patterson (1968). Heterosis was expressed as percent increase or decrease observed in the F_1 over the mid-parent as per the formula of Singh and Narayanan *et al*. (2016). The significance of F_1 hybrids from mid-parent and better-parent heterosis was determined using a t-test (Iqbal *et al*., 2009).

RESULTS AND DISCUSSION

Mean performance of parents and hybrids for yield and nutritional characters were recorded and presented in **Table 2**. In general, the performance of hybrids for yield and nutritional traits were found to be superior than the parents. Grain yield of the genotypes ranged from 22.31g (*Kalanamak*) to 43.81g (*Chinkinikar*/*Thandipallian*). Three out of six parents *viz*., CO54 (31.57g), *Thandipallian* (31.40g) and ADT56 (29.93g) had higher grain yield and the hybrids namely *Chinkinikar*/*Thandipallian* (43.81g), TPS5/*Chinkinikar* (42.25g), CO54 /*Kalanamak* (39.96g) and ADT56/*Kalanamak* (38.82g) recorded high grain yield per plant. The genotypes having more than 12.00 mg kg^{-1}

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Table 1. List of six rice genotypes parents used in present study

Parents no.	Genotype	Parentage	Features	Source
P_1	ADT56	WGL1437/ MDU5	Short duration, good cooking & eating qualities. Moderately resistant to leaf blast, grain discoloration, stem borer and leaf folder.	TRRI,Aduthurai
P_2	CO54	CB 04110/ CB 05501	White Medium slender rice. Moderately resident to Blast, Sheath rot, Brown Spot and BPH	Coimbatore, TNAU
P_3	TPS5	ADT 16 / ADT37	Short bold white rice, good in quality and also suitable for idly making. Moderately resistant to stem borer, leaf folder, gall midge, BPH and WBPH.	Tirupathisaram
P_4	*Kalanamak*	Landrace	Short duration, Finest quality, resistant to blast. Cooked rice is fluffy, soft, non-sticky, sweet, and easily digestible with relatively longer shelf-life. It had 15.6 mg kg-1 of iron. It is famous for taste, palatability, and aroma.	TRRI,Aduthurai
P_5	*Chinkinikar*	Landrace	Short duration, grain colour – red long bold, low gel consistency. Zn (26.4 mg kg-^{1}), Fe (16.10 mg kg-^{1}) and protein (10)	TRRI,Aduthurai
P_6	*Thandipallian*	Landrace	Short duration, grain colour – red long bold, low amylose content, It had 12.6 % protein	TRRI,Aduthurai

of Fe, 24.00 mg kg^{-1} of Zn and 10.00 per cent protein are considered as nutritional rich varieties for Fe, Zn and content respectively. In this study analysis of these nutritional composition among the genotypes reveals that, the parents *viz*., *Kalanamak* and *Chinkinikar* registered high Fe (15.60mg kg^{-1}) and Zn (26.40mg kg^{-1}) content respectively, where as high protein per cent of 12.06 registered by *Thandipallian.* Iron content of the hybrids ranged from 9.30 to 15.97mg kg^{-1} while, the Zinc content ranged from 14.00 to 26.74mg kg^{-1}and 9.33 to 12.33% for protein content. The highest Fe content in the parent has been recorded by *Kalanamak* (15.60mg kg^{-1}), which is serving as a National check variety for high iron content. Therefore, exploitation of the hybrids such as ADT56/ *Thandipallian*, ADT56/*Kalanamak*, CO54/*Thandiapllian* and CO54/*Kalanamak* would lead to identification of bio-fortified segregants with high yield.

ANOVA for combining ability is divided into general combining ability variance and specific combining ability variance (**Table 3**). Significant differences were observed among 21 genotypes for all the characters except for flag leaf width. Mean sum of squares due to general combining ability (GCA) and specific combining ability (SCA) were significant for all the characters except flag leaf width, indicated importance of both additive and non-additive gene action for the expression of all the traits except flag leaf width. However, variance due to GCA and SCA ratio showed preponderance of non-additive gene than additive gene action for all the yield and nutritional characters. The GCA/SCA ratio was very variable and ranged from -0.18 for flag leaf width to 1.17 for zinc content of grain (**Table 4**). The ratio (more than unity 0.5) of GCA/ SCA was found for the characters *viz*., total number of grains per panicle, grain yield per plant, filled grains per panicle, panicle length and plant height. Similar results were reported by Verma and Srivastava (2004), Rukmini Devi *et al*. (2014), Rukmini Devi *et al*. (2018), Vange *et al*. (2020), Bassuony and Zsembeli, (2021) and Anusha *et al*. (2021). The ratio of GCA/SCA was more than one for Zn content, indicating predominance of additive variances for this trait.

The selection of suitable parents for hybridization is one of the most important steps in any breeding programme in the development of best F_1 hybrids and segregating generation. The General combining ability is the average performance of a parent in a a set of hybrid combinations and it acts as an indicator to select the best parents for hybridization programmes. Positive significant GCA effects were observed for *Kalanamak*, CO54, *Chinkinikar* and *Thandipallian* and are referred as best combiners (**Table 4 and Fig. 1**).Besides this, the parents CO54, *Kalanamak*, *Thandipallian* along with ADT 56 were also adjudged as best parents based on mean performance of the hybrids. The above-mentioned best combiners had shown better performance for the morphological traits *viz*., number of productive tillers per plant, panicle weight, panicle length, filled grains, total number of grains per panicle, grain yield per plant and length to breadth ratio along with nutritional traits namely Fe, Zn and Protein content. On the other hand, the varieties ADT56 and TPS5 were found to be the good general combiners for earliness, plant height based on negative GCA effects. Similar findings were reported by Rukmini Devi *et al*. (2018), Azad *et al*. (2022) and Lal *et al*. (2023).

Specific combining ability, which results from a non-additive gene effect, is the deviation from the performance

Table 2. ***Per se*** **performance of parents and their hybrids**

S. No.	DFF	PH	NPT	FL	FW	PW	PL	FG	UFG	TNG	SPY	L/B	Fe	Zn	Pr
P1	81.00	104.33	15.00	34.50	1.17	2.23	25.77	244.67	48.33	243.00	29.93	3.66	11.36	16.83	11.67
P2	76.67	99.00	16.67	29.40	1.83	2.10	23.87	239.00	90.67	329.67	31.57	2.90	10.57	17.53	11.10
P3	65.33	105.00	17.33	22.47	1.40	2.78	24.00	201.00	78.00	279.00	28.80	3.53	10.87	20.07	10.27
P4	71.00	103.67	12.00	39.93	1.13	2.32	28.23	162.00	90.00	252.00	22.31	3.27	15.60	21.27	11.44
P5	83.67	177.67	23.00	45.23	1.40	2.94	29.80	129.00	25.00	154.00	28.79	2.07	11.28	26.40	11.19
P6	83.33	181.33	23.00	45.23	1.40	3.12	29.80	151.67	41.33	153.00	31.40	2.21	11.89	22.67	12.06
P1 x P2	76.33	97.33	18.00	32.50	1.37	2.52	27.70	232.00	41.67	273.67	33.00	3.51	9.30	14.87	9.78
P1 x P3	70.67	93.33	17.00	33.17	1.00	2.93	22.77	237.33	61.67	299.00	32.22	3.46	11.33	16.80	10.00
P1 x P4	72.33	108.17	23.00	30.17	1.20	2.63	31.27	218.00	58.67	257.67	38.82	3.33	15.97	19.33	10.67
P1 x P5	86.33	145.67	45.33	33.83	1.17	2.86	29.53	197.67	67.00	264.67	33.46	3.00	14.57	20.43	10.00
P1 x P6	82.67	183.67	23.00	22.40	1.73	3.55	27.83	178.33	75.33	253.67	35.03	2.51	12.63	26.54	12.33
P2 x P3	75.67	115.33	15.33	33.00	1.20	3.71	26.53	216.67	70.00	286.67	31.70	2.75	11.93	16.57	9.43
P2 x P4	69.33	92.67	12.67	29.13	1.27	2.68	24.83	202.67	86.67	279.33	39.96	2.66	15.57	22.74	9.99
P2 x P5	72.33	110.00	19.00	23.43	1.17	1.94	26.23	133.33	81.67	215.00	37.27	3.62	14.98	26.16	9.83
P2 x P6	82.67	139.33	17.67	35.67	1.27	2.47	27.00	177.33	63.33	240.67	36.32	3.00	12.19	23.20	10.03
P3 x P4	72.33	102.00	20.33	29.33	1.83	3.10	25.07	184.67	54.67	239.33	38.00	3.32	13.07	18.67	11.17
P3 x P5	80.67	138.33	21.00	35.90	1.57	3.00	27.50	141.67	55.00	196.67	42.25	2.46	11.94	26.74	10.14
P3 x P6	83.67	126.00	22.00	35.00	1.23	3.29	29.27	143.33	22.00	165.33	37.88	3.01	10.97	23.20	11.50
P4 x P5	81.00	147.67	37.00	37.53	1.00	2.32	29.23	219.67	22.00	241.67	36.27	2.25	13.33	26.33	10.96
P4 x P6	78.67	155.67	31.00	36.50	1.20	2.55	33.30	201.00	60.00	261.00	34.70	2.37	12.67	22.67	11.44
P5 x P6	84.67	165.67	45.33	32.50	1.17	2.89	31.20	164.33	77.00	241.33	43.81	3.00	12.90	23.77	11.00
MEAN	79.30	145.99	22.60	33.24	1.46	2.68	27.46	189.30	60.47	244.11	33.86	2.94	12.67	19.66	10.71
Mini	65.33	92.67	12.00	22.40	1.00	1.94	22.70	129.00	22.00	153.00	22.31	2.07	9.30	14.00	9.33
Max	86.33	183.67	45.33	39.93	1.83	3.71	33.30	244.67	90.00	329.67	43.81	3.66	15.97	26.74	12.33
C.V.(%)	1.97	9.55	35.78	22.9	109.07	11.57	8.42	11.19	15.99	9.50	20.79	7.38	8.77	8.41	7.71
SE.d	1.91	9.73	5.74	5.97	1.3	0.19	1.77	17.98	7.51	18.94	9.72	0.17	0.96	1.22	0.67

DFF: Days to 50% flowering; PH: Plant height; NPT: Number of productive tillers; FL: Flag leaf length; FW: Flag leaf width; PW: panicle weight; PL: panicle length; FG: Filled grains; UFG: unfilled grains; TNG: Total number of grains; SPY: Single plant yield; L/B: Length to breadth ratio; Fe: Iron; Zn: Zinc; Pr: Protein

P_1 : ADT56; P_2: CO54; P_3: TPS5; P_4: *Kalanamak*; P_5: *Chinkinikar*; P_6 : *Thandipallian*

Table 3. Analysis of variance for 15 traits

Source of variation	Replication	Genotypes	GCA	SCA	Error	GCA	SCA	GCA/SCA
Df	2	20	5	15	40			
DFF	19.97	65.98**	52.88**	27.25**	5.5	24.38	92..42	0.25
PH	116.08	2955.88**	2601.8**	446.43**	142.23	457.89	399.02	0.8
NPT	23.11	216.01**	97.49**	63.5**	49.44	17.62	46.02	0.21
FL	33.44	145.59**	100.27**	31.28**	53.5	9.36	13.44	0.76
FW	3.07	2.76	0.57	1.03	2.55	-0.03	0.18	-0.18
PW	0.35	1.99**	1.18**	1.35**	0.05	0.02	1.36	0.05
PL	7.66	39.76**	21.08**	7.31**	4.73	1.68	5.73	0.64
FG	12.32	4261.17**	2036.07**	836.07**	540.58	231.98	4746.08	0.56
UFG	322.49	1359.31**	496.05**	445.45**	94.66	145.97	657.23	0.22
TNG	0.42	638.65**	556.45**	1176.13**	616.24	531.37	4370.71	0.51
SPY	66.07	277.51**	152.88**	71.57**	141.05	13.24	33.98	0.55
L/B	0.04	0.81**	0.44**	0.21**	0.04	0.05	0.19	0.27
Fe	3.71	11.98*	3.15**	3.73**	1.39	0.37	3.27	0.11
Zn	4.16	26.85*	25.24**	4.42**	2.25	2.56	3.65	1.17
Pr	0.46	2.74**	0.96**	0.47**	0.68	0.04	0.34	0.23

*, ** Significant at 5% and 1% level, respectively

DFF: Days to 50% flowering
PH: Plant height
NPT: Number of productive tillers
FL: Flag leaf length
FW: Flag leaf width
PW: panicle weight
PL: panicle length
FG: Filled grains
UFG: unfilled grains
TNG: Total number of grains
SPY: Single plant yield
L/B: Length to breadth ratio
Fe: Iron
Zn: Zinc
Pr: Protein

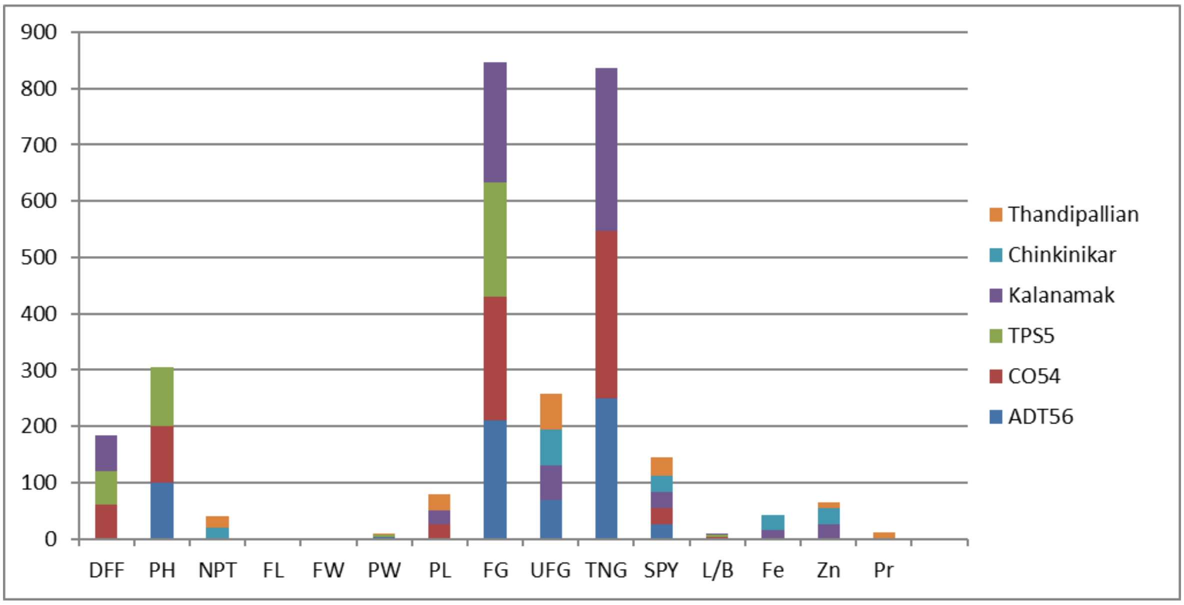

Fig. 1. List of best combiners among six parents

Table 4. General combining ability (GCA) effects parents for yield and nutritional traits

Parents	P_1	P_2	P_3	P_4	P_5	P_6
DFF	3.78 **	-3.18 **	-5.18 **	-4.93 **	6.53 **	2.99 **
PH	-6.92 **	-13.40 **	-24.19**	76.94 **	22.90 **	16.10 **
NPT	-2.15	-5.28 **	-3.90**	1.68	6.93 **	3.22 *
FL	-1.37	-4.00**	-3.55*	1.37	2.86 *	4.70**
FW	-0.27	-0.08	0.46	0.27	-0.16	-0.16
PW	0.17 *	-0.08	0.18**	-0.35**	-0.07	0.19 **
PL	-1.22 **	1.45 **	-2.24 **	2.35 **	0.28	2.28 **
FG	16.60 **	18.11 **	4.83 **	18.14 **	-12.44**	-22.57**
UFG	-5.44 **	17.81 **	2.47	-9.51 **	-14.15**	-10.19**
TNG	15.71 *	30.12 **	4.54	24.87 **	-26.04**	-32.21**
SPY	5.77*	12.61**	-4.73 *	4.31*	6.02 *	7.79**
L/B	0.19 **	0.12 *	0.16 **	0.10 **	-0.41 **	-0.17 **
Fe	-0.56 *	-0.49 *	-0.6**	1.03 **	0.67**	0.56
Zn	-2.24**	-1.28**	-0.59 *	0.70 *	1.74 **	2.67 **
Pr	0.14	-0.47**	-0.32*	0.28	0.31	0.43**

*, ** Significant at 5% and 1% level, respectively

P_1 : ADT56 P_3: TPS5 P_5: *Chinkinikar*
P_2: CO54 P_4: *Kalanamak* P_6: *Thandipallian*

DFF: Days to 50% flowering FL: Flag leaf length PL: panicle length TNG: Total number of grains Fe: Iron
PH: Plant height FW: Flag leaf width FG: Filled grains SPY: Single plant yield Zn: Zinc
NPT: Number of productive tillers PW: panicle weight UFG: unfilled grains L/B: Length to breadth ratio Pr: Protein

predicted on the basis of the parents' general combining ability. It is a crucial factor in the assessment of hybrids. Specific combining ability effects are used to evaluate the usefulness of cross combinations in exploiting heterosis (**Table 5**). Four hybrids *viz., Kalanamak*/*Chinkinikar*, *Chinkinikar*/*Thandipallian*, ADT56/*Kalanamak* and CO54/*Kalanamak* registered significant SCA effects for grain yield/plant. These cross combinations registered significant positive SCA effects for other yield traits *viz*., effective tillers per plant, panicle weight, filled grains, total number of grains per panicle, single plant yield and length to breadth ratio. Crosses showing high SCA effect involved either both or one good general combining parents and they can be successfully exploited for varietal improvement and are expected to throw stable performing transgressive segregants carrying fixable gene effects. Similar findings have been reported by Gnanamalar and Vivekanandhan (2013) and Rukmini Devi *et al*. (2018).

Negative SCA effects for days to 50% flowering and plant height is favorable and used for development of short duration varieties and semi dwarf varieties to avoid lodging. The combinations ADT 56/*Kalanamak*, CO54/*Chinkinikar* and CO54/*Kalanamak* were observed to possess negative SCA effect for days to 50% flowering. TPS5/*Thandipallian* and ADT56/CO54 displayed negative and significant SCA effects and were found to be good hybrids for dwarf plant stature. These four hybrids could be used to develop short-duration varieties. The negative SCA effects for flowering and plant height has also been reported by Rukmini Devi *et al*. (2018) and Azad *et al*. (2022).

In the present study the cross combinations *viz*., CO54/*Chinkinikar* (3.51%), CO54 /*Kalanamak* (3.45%), ADT56/*Kalanamak* (2.93%), were identified with positives significant SCA effects for Fe concentration. The crosses such as CO54/*Kalanamak* (1.52%),CO54 /*Chinkinikar* (1.19%) and TPS5/*Chinkinikar* (1.37%) had positive significant SCA effects for Zinc content. For protein, the crosses TPS5/*Chinkinikar* (2.15%) and ADT56/*Thandipallian* (1.96%) had positive significant SCA effects. Besides nutritional traits, these hybrid combinations also registered positive SCA effects for yield traits *viz*., panicle weight, panicle length, number of productive tillers, filled grains per panicle, total number of grains per panicle, grain yield per plant and L/B ratio. Therefore, these hybrids can be further utilized for simultaneous improvement of yield and nutritional traits in rice.

The results for relative heterosis and heterobeltiosis are furnished in **Table 6**. Negative heterosis for days to 50% flowering and plant height is desirable for developing short duration and short statured rice varieties to avoid lodging tendency. Out of 15 hybrids, three F_1s *viz*., ADT56/*Kalanamak* (-215%, -1.28%), CO54/*Chinkinikar*

Table 5. Specific combining ability (SCA) effects of crosses for yield and nutritional traits

Crosses	P1 x P2	P1 x P3	P1 x P4	P1 x P5	P1 x P6	P2 x P3	P2 x P4	P2 x P5	P2 x P6	P3 x P4	P3 x P5	P3 x P6	P4 x P5	P4 x P6	P5 x P6
DFF	0.34	-7.23 **	-5.82 **	4.26**	-5.79**	3.38**	-2.37**	-10.32 **	-0.99	0.21	-0.37	-0.41	3.55**	1.17	-4.15 *
PH	-19.47**	-0.35	-71.88	42.90**	-18.64**	5.46	-6.89	-8.29	11.84*	-4.1	-25.16**	-33.04**	-5.51	9.28	-18.12**
NPT	3.61	0.4	3.82	16.10**	-7.72*	-3.3	5.78**	-5.47	-2.1	2.9	-5.68	-5.3	11.40**	3.11	18.20**
FL	-1.73	6.16	-1.76	-11.03**	-12.03 **	-1.91	-5.87	-10.07 **	3.04	-2.75	4.65	-1.41	1.36	-1.5	-5.66
FW	-0.08	-0.59	-0.26	0.17	0.29	-0.52	-0.49	0.01	0.04	3.44**	-0.13	-0.47	-0.57	-0.38	0.02
PW	0.55	-0.70**	0.64**	-0.74**	0.38**	0.12	0.36**	-1.51**	-0.57**	0.12	0.37**	0.25	-0.49**	-0.52**	0.26*
PL	-1.44	-1.59	4.31**	-5.71**	-0.34	0.37	-0.69	1.29**	-1.64	-0.87	-2.36*	-0.86	-1.22	2.85**	1.16
FG	-6.92	28.33**	26.07**	12.62	34.75**	-4.53	48.79**	33.21**	-2.42	-28.54**	-40.96**	-13.50**	50.42**	34.79**	37.54**
UFG	-17.25**	4.48	-8.04	-18.63**	24.08**	-6.5	9.46**	28.21**	-4.50**	-10.54**	20.12	-30.50**	-34.92**	-2.54	41.46**
TNG	-24.64	17.39**	35.06**	28.52*	28.36**	1.52	-6.48	-41.89**	-4.39**	-16.23	-21.31*	-52.52*	13.36	38.48**	57.50**
SPY	5.95*	-10.59	22.04**	8.31	9.58	7.97	15.93**	-5.17	-2.66	13.02	-17.24*	8.42	35.71**	4.61	26.89**
L/B	0.26**	0.60	0.09	-0.21	-0.21*	-0.60**	-0.45 **	0.35**	0.26**	0.21*	-0.40**	0.80	-0.39**	-0.51**	0.63**
Fe	-2.56	-0.72	2.93**	1.52**	-0.33	-0.58	3.45**	3.51**	-0.09	0.36	-1.41*	2.64**	-0.87	- 0.93	2.37**
Zn	-1.84**	0.87	1.31	-1.65	-2.42**	-0.75	-2.02**	1.19**	3.26**	-1.02	1.48*	-1.37	1.52**	0.74	-2.52**
Pr	-0.81	-0.44	0.37	-1.26**	1.96**	-0.41	-0.83	0.31	-0.18	0.58	-3.47*	2.15**	-0.45*	0.37	-0.06

*, ** Significant at 5% and 1% level, respectively

P_1 : ADT56
P_2: CO54
P_3: TPS5
P_4: *Kalanamak*
P_5: *Chinkinikar*
P_6 : *Thandipallian*

DFF: Days to 50% flowering
PH: Plant height
NPT: Number of productive tillers
FL: Flag leaf length
FW: Flag leaf width
PW: panicle weight
PL: panicle length
FG: Filled grains
UFG: unfilled grains
TNG: Total number of grains
SPY: Single plant yield
L/B: Length to breadth ratio
Fe: Iron
Zn: Zinc
Pr: Protein

(-1.46%, -3.98%) and ADT56/*Thandipallian* (-1.68%, -3.31%) displayed negative and significant mid and better parent heterosis for days to 50% flowering and plant height respectively. For the morphological trait number of productive tillers, two hybrids *viz.*, *Kalanamak/Chinkinikar* (111.43%, 60.87%) and *Chinkinikar/Thandipallian* (97.10%, 97.87%) shown positive and significant heterosis over their mid, better parent heterosis respectively. The four hybrids ADT56/*Kalanamak* (23.67%, 17.94%), ADT56/*Thandipallian* (66.74%, 66.37%), TPS5/*Chinkinikar* (28.28%, 25.72%) andTPS5/*Thandipallian* (26.28%, 20.12%) registered for panicle weight. Three F_1s such as ADT56/*Kalanamak* (40.30%, 46.78%), CO54/*Kalanamak* (40.51%, 37.16%) and TPS5/*Thandipallian* (29.89%, 17.41%) recorded for filled grains per panicle. Three combinations AD56/*Kalanamak* (31.42%, 26.05%),

Table 6. Estimates of Heterosis and heterobeltiosis of crosses for yield and nutritional traits

Cross	Days to 50% flowering		Plant height		Number of tillers/ plant		Flag leaf length		Flag leaf width		Panicle weight	
	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP
P1 x P2	-3.71	0.57	-19.43 *	-20.31 *	15.00	-6.90	-22.27	-28.02	-31.11	-43.64	-34.57 **	-36.47 **
P1 x P3	-3.95**	3.08	-10.83	-11.11	-23.64	-27.59	16.44	-3.86	-22.08	-28.57	-27.09 **	-30.79 **
P1 x P4	-2.15**	-1.28 *	-10.45**	-32.10 *	46.81*	18.97	-18.94	-24.46	4.35	2.86	23.67 **	17.94 *
P1 x P5	3.99**	3.42 *	30.26**	3.38	-35.43	-40.58	-43.81 **	-50.48**	-6.49	-14.29	-38.69 **	-40.66**
P1 x P6	-1.68	-3.31 *	-19.25**	-36.40**	-38.58	-43.48	-17.22	-27.04 *	3.90	-4.76	66.74 **	66.37 **
P2 x P3	3.81**	3.08	-12.44	-13.13	-45.10	-46.15	-13.37	-23.58	-21.65	-30.91	1.38	-0.95
P2 x P4	-1.14*	-0.28	-8.97*	-18.52 *	32.56	14.00	-32.40 *	-41.32**	-21.35	-36.36	35.00 **	-36.19**
P2 x P5	-1.46*	-3.98 *	-11.37*	-29.08 **	22.69**	- 33.33	-29.43 *	-41.78**	-23.71	-32.73	19.55**	9.21
P2 x P6	-0.98	-2.48	-3.24	-23.16 **	-10.92	-23.19	-4.42	-21.15	-21.65	-30.91	-31.79 **	-33.63**
P3 x P4	1.98**	0.84	-15.00 *	-24.44 **	38.64	17.31	-13.46	-32.39 *	-339.47**	-97.62*	4.14	3.62
P3 x P5	-2.46**	-0.84	-30.42**	-44.65 **	-28.93	-37.68	6.06	-20.63	11.90	11.90	28.28 **	25.72**
P3 x P6	-1.83**	0.00	-41.56**	-23.86 **	-32.23	-40.58	-6.45	-29.99 *	-11.90	-11.90	26.28 **	20.12 *
P4 x P5	3.42 **	3.15	-5.54	-16.89 **	111.43**	60.87 *	-11.86	-17.02	-21.05	-28.57	-35.93 **	-36.90**
P4 x P6	1.69	-0.28	-1.58	-14.15 *	58.10 *	20.29	-14.29	-19.31	-5.26	-14.29	-27.10 **	-30.33**
P5 x P6	4.45 **	0.28	-18.85**	-19.67 **	97.10 **	97.87 **	-25.20 *	-25.20	-16.67	-16.67	-12.23	-14.86

Table 6. Conti…

Cross	Panicle length		Filled grains		Unfilled grains		Total number of grains		SPY	
	MP	BP	MP	BP	MP	BP	MP	BP	MP	BP
P1 x P2	-16.54 *	-19.40 **	-29.40 **	-36.40 **	-40.05 **	-54.04 **	33.26 *	-41.25 **	-49.27 *	-54.97 *
P1 x P3	15.80 **	10.74	-57.88**	58.54 **	-76.25 **	-80.77**	-32.34 *	-64.76 **	-70.79 **	-77.72 **
P1 x P4	-31.01**	-35.68 **	40.30**	46.78 **	-15.07 **	-7.37	31.42 *	26.05 **	28.14 **	28.07*
P1 x P5	-4.50	-10.96	4.02	-13.53	-16.48	-47.59**	33.26**	20.30 *	-45.19 *	-47.82 *
P1 x P6	-5.99	-6.25	34.25 **	9.08	25.00	-6.90	77.06 **	5.90	-40.96	-48.51 *
P2 x P3	0.70	-7.08	-36.67**	-41.70 **	-13.04	-19.12 *	46.33**	-35.49 **	-57.85	-64.64 *
P2 x P4	-3.35	-12.98 *	30.51**	37.16 **	-67.17 **	-36.03 **	41.06**	-37.82 **	35.45 **	27.78 **
P2 x P5	-6.83	-16.11 **	47.46**	-39.55 **	-57.28 **	-75.74**	48.35**	64.00 **	28.94% *	-55.34 *
P2 x P6	-4.02	-11.22	-73.75**	-80.20 **	-53.35 **	-70.59 **	-49.08 **	-77.55 **	-76.73 **	-77.19 *
P3 x P4	-20.07**	-27.85 **	-40.10**	-45.84 **	-60.38 **	-64.10**	11.93	45.54 **	20.46	-4.46
P3 x P5	-7.06	-16.11 **	34.44**	-39.39 **	-51.77 *	-29.49 **	32.92**	-47.43 **	41.97*	54.12 *
P3 x P6	-6.15	-8.61	29.89 *	17.41*	-63.93 **	-76.50 **	26.83*	-33.93 **	0.41	-14.36
P4 x P5	14.76 **	11.74	16.33	-11.66	-41.85 *	-65.26 **	66.28 **	19.08 **	29.11 **	-38.44 *
P4 x P6	-0.89	-0.89	-54.46**	-66.09 **	-0.38	-31.58 *	-12.16	-57.25 **	-7.37	-15.23
P5 x P6	-12.56 *	-15.78 *	-43.35**	-44.96**	103.70 **	89.01 **	-7.34	-7.34	23.82	12.89

Table 6. Conti…

Cross	L/B ratio		Fe		Zn		Pr	
	MP	BP	MP	BP	MP	BP	MP	BP
P1 x P2	7.12	-4.01	-18.21 *	-21.07 *	-17.36 **	-19.01 **	-14.64 **	-16.71 **
P1 x P3	-25.23 **	-26.53**	1.98	-0.23	-8.94	-16.28 *	-8.80	-14.26 *
P1 x P4	-3.99	-9.02	19.08 **	14. 58 **	13.49*	-9.09	-7.63	-8.54
P1 x P5	-12.34 *	-31.36**	11.59	11.21	-7.46	-19.77 **	7.90	5.71
P1 x P6	-6.20	-24.79 **	2.65	0.36	-16.12 **	-26.91 **	17.08 **	19.14 **
P2 x P3	-18.26 **	-25.59**	-3.73	-5.06	-25.53 **	-30.23 **	-9.62	-13.00 *
P2 x P4	17.34 **	10.59 *	18.14 **	21.46 **	12.58 *	-20.25 **	-12.73 *	-14.02 *
P2 x P5	21.07 **	3.80	16.15 **	19.51 **	24.66 **	29.97*	-1.32	-1.73
P2 x P6	17.70 **	3.68	8.53	2.50	11.42 **	2.35	-9.56	-9.61
P3 x P4	-2.40	-5.95	10.34	1.95	-9.68	-12.23 *	2.89	-2.36
P3 x P5	-12.26 *	30.41 **	7.81 *	5.82	-4.59	10.55**	15.48 **	-9.38
P3 x P6	30.16 **	5.76	-30.66 **	-25.04 **	2.96	-2.94	-3.64	7.19 *
P4 x P5	-15.91 **	-31.36 **	10.65	4.03*	1.06	-2.62	-3.14	-4.17
P4 x P6	-13.38 *	-27.49 **	2.54	-1.17	3.19	0.00	-1.38	-2.89
P5 x P6	35.14 **	35.80 **	23.72 **	16.51 **	-10.38 *	-10.90 *	-10.23	-10.66

*, ** Significant at 5% and 1% level, respectively

P1: ADT56
P2: CO54
P3: TPS5
P4: *Kalanamak*
P5: *Chinkinikar*
P6: *Thandipallian*

DFF: Days to 50% flowering
PH: Plant height
NPT: Number of productive tillers
FL: Flag leaf length
FW: Flag leaf width
PW: panicle weight
PL: panicle length
FG: Filled grains
UFG: unfilled grains
TNG: Total number of grains
SPY: Single plant yield
L/B: Length to breadth ratio
Fe: Iron
Zn: Zinc
Pr: Protein

ADT56/*Chinkinikar* (33.26%, 20.30%) and CO54/*Chinkinikar* (48.35%, 64.00%) displayed for number of grains per panicle. For the yield contributing trait, grain yield per plant, only three hybrids *viz.*, ADT56/*Kalanamak* (28.14%, 28.07%), CO54/*Kalanamak* (35.45%, 27.78%) and TPS5/*Chinkinikar* (41.97%, 54.12%) showed positive and significant heterosis over mid and better parent.

The results for nutritional traits showed positive and significant heterosis for Fe. Out of 15 F_1s, four crosses namely, ADT56/*Kalanamak* (19.08%, 14.58%), CO54/*Kalanamak* (18.14%, 21.46%), CO54/*Chinikinikar* (16.15%, 19.51%) and *Chinkinikar*/*Thandipallian* (23.72%, 16.51%) shown positive and significant heterosis over mid and better parent for Iron content. The hybrid CO54/*Chinkinikar* (24.66%, 29.97%) recorded positive and significant mid and better parent heterosis for zinc content respectively. On the other-hand the cross TPS5/*Chinkinikar* (15.48%) has shown positive and significant for mid parent heterosis only. The F_1 TPS5/*Thandipallian* had positive and significant for protein (17.08%, 19.14%) over their mid and better parent heterosis respectively. Similar results reported by Anusha *et al.*(2021) and Hussein *et al.*(2021) and Lal *et al*. (2023).

Hybrids were evaluated for standard heterosis based on performance over the standard check variety CO54 and the same is presented in **Table 7** and promising hybrids were selected. Four F_1 crosses, ADT56/*Kalanamak*, ADT56/*Thandipallian*, CO54/*Kalanamak* and CO54/*Chinkinikar* recorded positive and significant standard heterosis over standard check CO54 with regards to yield characters and nutritional traits. The crosses *viz.,* ADT56/*Kalanamak* (23.30g), CO54/*Kalanamak* (31.20g) and CO54/*Chinkinikar* (25.70g) recorded positive and significant standard heterosis for grain yield per plant. For the traits, filled and total number of grains per panicle, two out of above mentioned four crosses *viz.,* ADT56/*Kalanamak* (28.77%, 31.42%) and CO54/*Kalanamak* (32.88%, 41.06%) recorded positive and significant standard heterosis. For nutritional traits, three hybrids *viz.,* ADT56/*Kalanamak* (24.58%), CO54/*Kalanamak* (21.46%) and CO54/*Chinkinikar* (24.56%) recorded positive and significant standard heterosis for Fe only. On further breeding endeavors, these hybrids are useful in the development of bio-fortified high yielding rice varieties.

In the present study on the basis of *per se* performance, GCA effects and heterosis for seed yield per plant and

Table 7. Estimates of Standard heterosis of crosses for yield and nutritional traits

S.No.	DFF	PH	NPT	FL	FW	PW	PL	FG	UFG	TNG	SPY	L/B	Fe	Zn	Pr
P1 x P2	-2.48	-53.13 **	-21.74	45.10 **	-26.19	-36.19 **	-27.18 **	24.93	76.06 *	33.26 *	-39.51	59.06 **	-30.04 **	-38.08 **	-12.36 *
P1 x P3	1.38	-48.53 **	-39.13	26.68 *	-28.57	-30.48 **	-30.31**	-31.51 *	-36.62*	-32.34 *	-40.07 *	21.75**	-11.57	-26.74 **	-9.77
P1 x P4	-3.58 *	-27.11 **	0.00	33.31 *	-14.29	18.47 *	4.92	28.77*	-47.89 **	31.42 *	23.37 *	50.76 **	24.58 **	-15.70 **	-3.76
P1 x P5	0.00	1.29	-40.58	50.48 **	-14.29	-40.39**	35.68 **	38.36 *	7.04	33.26 *	-29.90	13.75	-1.43	-19.77 **	11.24
P1 x P6	-3.31 *	-36.40 **	-43.48	27.04 *	-4.76	67.12 **	-10.96	-74.52**	90.14 **	77.06 **	-30.83	24.62 **	-6.89	-27.76 **	-14.91 *
P2 x P3	1.38	-48.90 **	-59.42 *	50.33 **	-9.52	-6.31	-24.50**	14.52	-29.86 **	46.33 **	-63.17 *	19.03 *	-19.51 *	-38.95 **	-12.90 *
P2 x P4	-3.31 *	-39.34 **	-17.39	48.19 **	-16.67	-39.64**	-11.97	32.88 *	-42.13 **	41.06 **	31.20 *	64.05 **	21.46 **	-26.05 **	-11.30
P2 x P5	-6.89 **	-30.51 **	-33.33	41.78 **	-11.90	3.30	-12.98 *	-20.55	-7.04	-18.35	25.76 *	36.25 **	24.58 **	1.16	-0.78
P2 x P6	-2.48	-23.16 **	-23.19	21.15	-9.52	-33.63**	-16.11**	-61.10 **	12.68	-49.08 **	-76.25 *	36.10 **	-4.92	1.16	-9.50
P3 x P4	-0.83	-43.75 **	-11.59	40.31 **	97.62**	5.56	15.88 *	10.68	-18.31*	11.93	15.04	50.45 **	1.95	-18.60 **	0.72
P3 x P5	-2.48	-45.77 **	-37.68	20.63	11.90	18.17 *	-27.85**	-24.66	-72.39 **	0.92	-44.28 **	11.33	-6.84	-10.55	-8.51
P3 x P6	0.00	-53.86 **	-40.58	29.99 *	-11.90	20.12 *	-16.11**	-36.44 *	-52.54 **	26.83	-14.36	69.18 **	15.99 *	-4.07	-7.19
P4 x P5	-0.83	-18.57 **	60.87 *	17.02	-28.57	-40.69**	-8.61	-80.55 **	-7.04	66.28 **	-32.41 **	1.81	4.03	-2.62	-1.14
P4 x P6	-0.28	-14.15 *	20.29	19.31	-14.29	-30.33 **	11.74	-30.68	83.10 *	-12.16	2.08	7.55	-1.17	-1.16	0.18
P5 x P6	0.28	-19.67 **	97.10 **	25.20	-16.67	-14.86	-15.89**	-41.64 *	169.01 **	-7.34	37.10*	35.80 **	22.51 **	-10.90 *	-9.80

*, ** Significant at 5% and 1% level, respectively

P1: ADT56 P3: TPS5 P5: *Chinkinikar*
P2: CO54 P4: *Kalanamak* P6: *Thandipallian*

DFF: Days to 50% flowering; PH: Plant height; NPT: Number of productive tillers; FL: Flag leaf length; FW: Flag leaf width; PW: panicle weight; PL: panicle length; FG: Filled grains; UFG: unfilled grains; TNG: Total number of grains; SPY: Single plant yield; L/B: Length to breadth ratio; Fe: Iron; Zn: Zinc; Pr: Protein other important yield attributes, the genotypes CO54, *Kalanamak* and *Chinkinikar* were identified as best general combiners and they provide ample scope for utilizing these genotypes to recombine unique characters such as short stature, earliness, high tillering capacity, filled and total number of grain per panicle and nutritional traits. The crosses ADT56/*Kalanamak*, CO54/*Kalanamak* and CO54/*Chinkinikar* had high per *se* performance, positive, significant SCA effects and heterosis for yield and nutritional traits. These hybrids serve as a useful breeding material in the development of high yielding, bio-fortified rice varieties with increased levels of micronutrients, to address the food and nutritional security of the rice consumers.

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