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Studies on combining ability for yield, its components and zinc content in rice (*Oryza sativa* L.)

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Abstract
A line x tester analysis was performed using three lines and eight testers, generating 24 hybrids, to evaluate the combining ability of parents for grain yield, yield-contributing traits, and zinc content in rice. Twelve traits were studied: days to 50% flowering, plant height (cm), panicle length (cm), effective tillers per plant, grains per panicle, length-to-breadth ratio, grain yield per plant (g), straw yield per plant (g), test weight (g), zinc content (ppm), protein content (%), and amylose content (%). The experiment was conducted in a randomized block design (RBD) with three replications at the Main Rice Research Station, Navsari Agricultural University, Navsari, during *kharif* 2024. The analysis of variance for combining ability indicated that general combining ability (σ^2GCA) effects were significant for grains per panicle, while specific combining ability (σ^2SCA) effects were significant for all traits except plant height and zinc content. The σ^2GCA/σ^2SCA ratio was less than one for all traits, suggesting that non-additive genetic variance played a predominant role in their inheritance.

Keywords: Rice, line × tester, general combining ability, specific combining ability

Introduction
Rice (*Oryza sativa* L.), a self-pollinated cereal crop (2n = 24) belonging to the family *Poaceae*, is the staple food for more than half of the world's population and forms the backbone of food and nutritional security. It is cultivated in over 100 countries, with Asia contributing nearly 90% of the total production. India ranks first in rice area and second in production after China. As a primary dietary energy source, rice contributes nearly 700 kcal/day to around three billion people. Besides starch, it also supplies protein, iron, zinc, and vitamins like thiamine and niacin (Fukagawa and Ziska, 2019) [1]. However, polished white rice, which is preferred for cooking and appearance, loses a considerable proportion of its nutrients during milling, including a drastic reduction in zinc and other micronutrients (Modgil and Rani, 2016) [2].

Zinc is an essential micronutrient required for human health, plant growth, and overall ecosystem balance. In humans, zinc is a cofactor for over 300 enzymes and plays a critical role in the synthesis of proteins, regulation of hormones, immune system functioning, and metabolism of carbohydrates and nucleic acids. Its deficiency causes severe health consequences such as stunted growth, impaired cognitive development, weakened immunity, and complications in maternal and child health. The World Health Organization identifies zinc deficiency as the fifth most significant contributor to disease burden in developing countries, affecting nearly one-third of the global population (Cakmak, 2008) [3]. Every year, zinc deficiency is linked to more than 116,000 child deaths globally. The recommended daily intake ranges between 7-13 mg for adults to maintain proper physiological functions (Swamy *et al.*, 2016) [4]. In plants, 'zinc is required for enzyme activation, aux in metabolism, pollen development, and membrane stability. Deficiency in crops often results in reduced chlorophyll levels, poor grain filling, and lower productivity (Cakmak, 2008) [3]. Thus, enriching rice with zinc has dual benefits—improving crop yield and addressing human malnutrition.

To combat widespread zinc deficiency, biofortification of rice has become a sustainable and cost-effective strategy. This can be achieved through agronomic approaches (such as zinc fertilization and soil management) and genetic approaches (exploiting natural variation in zinc content). Breeding for zinc-enriched rice has gained momentum as genetic variation for grain zinc concentration is widely available in germplasm collections. Quantitative trait loci (QTLs) linked to zinc accumulation have been mapped, and marker-assisted selection is being used to integrate these traits into high-yielding cultivars (Swamy *et al*., 2016) [4]. Advances in molecular biology and genomics, including the identification of zinc transporter genes (such as *ZIP* and *HMA* families), offer further opportunities for targeted improvement. Combining conventional breeding with modern biotechnological tools has the potential to accelerate the development of zinc-biofortified rice varieties.

In addition, combining ability analysis remains a vital tool in rice breeding programs for selecting parents and crosses with superior performance for both yield and nutritional traits. It allows breeders to dissect additive and non-additive gene effects, guiding the choice of breeding strategies. The integration of zinc biofortification into mainstream rice improvement programs ensures that future varieties meet the dual goals of high productivity and enhanced nutritional quality.

Overall, breeding rice with elevated zinc content provides a long-term, sustainable solution to tackle hidden hunger, particularly in resource-poor populations dependent on rice as their staple food. By addressing zinc deficiency through biofortification, rice breeders contribute not only to improved human health but also to achieving global food and nutritional security targets.

Materials and Methods

The experimental material consisted of three female lines and eight male testers (Table 1) obtained from the Main Rice Research Centre, NAU, Navsari (20°37′ N latitude, 72°54′ E longitude, 11.98 m above mean sea level). These were crossed during *summer 2024* using the line x tester mating design to generate 24 hybrids. Each entry was sown in a single row of 12 plants with a spacing of 20 x 15 cm. All the cultural practices were followed as per requirements and recommendations. The crossing program was carried out through hand emasculation and pollination. Hybrid seeds along with selfed parental seeds were harvested, cleaned, and stored carefully in seed bags for sowing in the subsequent *kharif 2024* season.

Crossing was initiated at the commencement of flowering. Emasculation was performed on female spikelets likely to open the following day, while open, fully developed, and underdeveloped florets were removed. The top one-third of the selected spikelets was clipped, and the anthers were removed using an emasculation needle either in the evening or early morning, about 1-2 hours prior to pollination, ensuring the stigma remained undamaged. Emasculated spikelets were immediately covered with butter paper bags. On the next morning, after 9 a.m., fresh panicles from the selected male parent were collected and placed under artificial light to facilitate anther dehiscence. Pollination was performed by dusting the released pollen onto the stigmas of emasculated florets. Following pollination, the florets were re-covered with butter paper bags and tagged with the cross details (female x male) and the date.

The experimental crop was raised following recommended agronomic practices. For data recording, five competitive plants were randomly selected from each entry to measure all yield-contributing traits, except days to 50% flowering, which was recorded on a plot basis. The mean values were subjected to appropriate statistical analyses

Table 1: Details of experimental material

S. No.	Lines	Source
1	IET-31004	M.R.R.C, NAU, Navsari
2	IET-31027	M.R.R.C, NAU, Navsari
3	IET-31031	M.R.R.C, NAU, Navsari
	Testers	
1	DRR dhan 45	M.R.R.C, NAU, Navsari
2	GR-15 (Check)	M.R.R.C, NAU, Navsari
3	DRR dhan 48	M.R.R.C, NAU, Navsari
4	DRR dhan 49	M.R.R.C, NAU, Navsari
5	NVSR -1260	M.R.R.C, NAU, Navsari
6	GR-23	M.R.R.C, NAU, Navsari
7	GNR-2	M.R.R.C, NAU, Navsari
8	GNR-7	M.R.R.C, NAU, Navsari

M.R.R.C- Main Rice Research Centre, Navsari Agricultural University, Navsari

Results and Discussion

The analysis of variance for combining ability (Table 2) indicated that the mean sum of squares due to lines was non-significant for days to 50% flowering and plant height, whereas it was significant for the remaining traits. In the case of testers, significant mean sum of squares was observed for all the characters. The interaction effects (lines x testers) were also found to be significant for all the traits except days to 50% flowering.

The variance component due to general combining ability (σ^2GCA) was significant only for grains per panicle, while specific combining ability variance (σ^2SCA) was significant for all characters except plant height and zinc content. The ratio of σ^2GCA to σ^2SCA was less than unity for all the characters, suggesting the predominance of non-additive gene action in the inheritance of these traits. This trend is also illustrated in Figure 1 for all twelve traits studied. Furthermore, estimates of additive and dominance variances revealed that dominance variance was greater than additive variance for all traits. Hence, the improvement of such characters would be more effectively achieved through heterosis breeding.

Table 2: Analysis of variance for combining ability and variance components for different characters in rice

Source of variation	df	Days to 50 percent flowering	Plant height	Panicle length	Effective tillers per plant	Grains per panicle	L/B ratio
Replications	2	1.47	132.32	2.71	0.01	300.51	0.01
Hybrids	23	52.08**	194.80*	18.33**	6.96**	6244.12**	0.63**
Line effect	2	4.58	1.00	19.57**	4.39**	8102.32**	1.04**
Tester effect	7	60.79**	335.41**	18.87**	9.49**	10054.75**	0.62**
Line x Tester effect	14	54.50**	152.19	17.89**	6.07**	4073.36**	0.58**
Error	46	5.96	99.08	3.68	0.43	202.06	0.02
Variance components							
σ^2_A		-5.29	3.88	0.32	0.21	1213.38	0.06
σ^2_D		64.72	70.81	18.95	7.51	5161.73	0.75
σ^2_{GCA}		-1.32	0.97	0.08	0.05	303.34*	0.02
σ^2_{SCA}		16.18**	17.70	4.74**	1.88**	1290.43**	0.19**
$\sigma^2_{GCA}/\sigma^2_{SCA}$		-0.08	0.05	0.02	0.03	0.24	0.08

* and ** indicates significance at 5% and 1% levels of probability, respectively.

Table 2: Continue…

Source of variation	df	Grain yield per plant	Straw yield per plant	Test weight	Zn content	Protein content	Amylose content
Replications	2	5.20	0.40	0.43	0.47	0.11	1.27
Hybrids	23	60.94**	165.24**	16.58**	22.30**	1.92**	4.77**
Line effect	2	67.63**	128.39**	12.78**	10.10**	0.67**	10.57**
Tester effect	7	78.91**	138.29**	15.51**	34.22**	1.48**	4.15**
Line x Tester effect	14	50.99**	183.99**	17.67**	18.09**	17.66**	4.25**
Error	46	6.58	9.63	0.63	1.02	0.13	1.25
Variance components							
σ^2_A		5.40	-12.28	-0.85	0.99	-0.31	0.75
σ^2_D		59.22	232.48	22.72	22.75	2.93	4.00
σ^2_{GCA}		1.35	-3.07	-0.21	0.25	-0.08	0.19
σ^2_{SCA}		14.80**	58.12**	5.68**	5.69	0.73**	1.00**
$\sigma^2_{GCA}/\sigma^2_{SCA}$		0.09	-0.05	-0.04	0.04	-0.10	0.19

* and ** indicates significance at 5% and 1% levels of probability, respectively

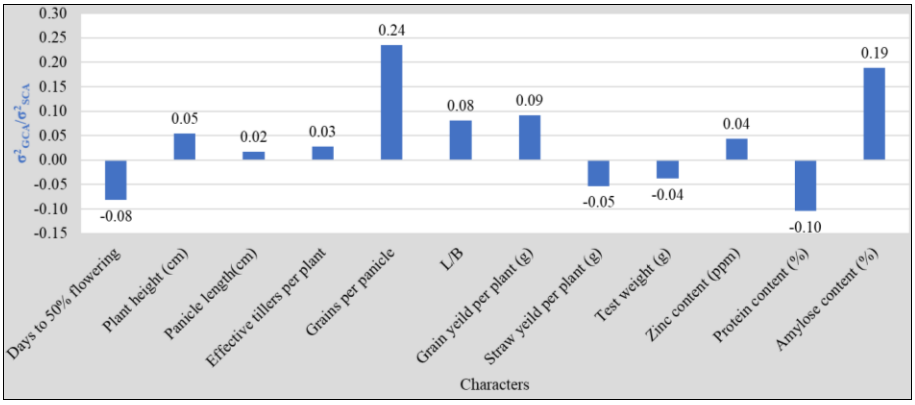


Fig 1: $\sigma^2_{GCA}/\sigma^2_{SCA}$ ratio of 12 characters in rice

The evaluation of combining ability effects plays an important role in identifying superior parents for use in future breeding programs. In the present study, estimates of general combining ability (GCA) revealed that no parent exhibited consistently high performance across all traits, indicating trait-specific combining ability. Based on their GCA values, parents were categorized as good, average, or poor combiners (Table 3). Parents with significant GCA effects in the desirable direction (positive or negative, depending on the trait) were classified as good general combiners, whereas those with significant but undesirable effects were categorized as poor combiners. Parents with non-significant effects were considered average combiners.

Among the female parents, all were identified as average general combiners. However, among the male parents, DRR Dhan 45 and NVSR 1260 emerged as good general combiners for grain yield per plant, making them potential candidates for use in yield improvement programs. The female parent IET 31004 showed good GCA for length-to-breadth ratio, while IET 31027 was a good combiner for grains per panicle. On the male side, DRR Dhan 45 exhibited favourable GCA effects for several traits including days to 50% flowering, effective tillers per plant, grains per panicle, grain yield, straw yield, test weight, and amylose content. NVSR 1260 was also a strong combiner, contributing positively to panicle length, effective tillers per plant, grains per panicle, L/B ratio, grain yield, test weight, and zinc content. These findings suggest that parents contributing positively to grain yield also tended to perform well for yield-related component traits (Table 4).

Estimates of specific combining ability (SCA) effects (Table 5) revealed that no hybrid was superior for all traits simultaneously. Out of the 24 hybrids, IET 31027 x DRR Dhan 45 and IET 31027 x NVSR 1260 demonstrated significant positive SCA effects for grain yield per plant. The hybrid IET 31027 x DRR Dhan 45 also expressed desirable SCA effects for grains per panicle, L/B ratio, straw yield, zinc content, and protein content. Similarly, IET 31027 x NVSR 1260 recorded favourable SCA effects for days to 50% flowering, grains per panicle, and test weight. Another promising cross, IET 31004 x DRR Dhan 45, showed significant SCA effects for effective tillers per plant, L/B ratio, straw yield, test weight, zinc content, and protein content. Specific combining ability (SCA) estimates further demonstrated that none of the crosses were superior for all the characters under investigation. However, the cross IET 31027 x NVSR 1260 exhibited a significant positive SCA effect for grain yield per plant, and the hybrid IET 31027 x DRR Dhan 48 was notable for its positive and significant SCA effect for zinc content. Different hybrids showed the highest significant SCA effects in the desired direction for various traits. For example, IET 31004 x GNR 7 and IET 31027 x NVSR 1260 were promising for days to 50% flowering, while IET 31031 x DRR Dhan 48 showed superiority for panicle length. Hybrids such as IET 31004 x DRR Dhan 45, IET 31027 x GNR 2, and IET 31031 x GR 23 were favourable for effective tillers per plant. For grains per panicle, significant positive SCA was observed in IET 31027 x NVSR 1260, IET 31031 x DRR Dhan 45, IET 31004 x GR 15, and IET 31031 x DRR Dhan 49.Similarly, IET 31004 x GR 23, IET 31004 x GNR 2, IET 31027 x DRR Dhan 49, IET 31027 x GNR 7, and IET 31031 x DRR Dhan 45 performed well for L/B ratio, while high SCA for straw yield per plant was noted in IET 31004 x DRR Dhan 45, IET 31004 x DRR Dhan 48, IET 31031 x DRR Dhan 45, IET 31031 x GNR 2, and IET 31031 x GNR 7. For test weight, the hybrids IET 31031 x GR 23, IET 31004 x GNR 7, IET 31027 x NVSR 1260, IET 31004 x DRR Dhan 45, IET 31027 x GNR 2, and IET 31031 x GR 15 were superior. For zinc content, desirable SCA effects were obtained in IET 31004 x DRR Dhan

45, IET 31004 x DRR Dhan 49, IET 31027 x DRR Dhan 48, and IET 31031 x GNR 7. For protein content, hybrids such as IET 31004 x NVSR 1260, IET 31004 x GR 23, IET 31027 x DRR Dhan 45, IET 31027 x DRR Dhan 49, IET 31031 x GR 15, and IET 31031 x DRR Dhan 48 showed significant positive SCA effects. GCA effect for grain yield per plant and zinc content of parents is shown in Fig. 2 and Fig. 3 respectively. SCA effect for grain yield per plant and zinc content of parents is shown in Fig. 4 and Fig. 5 respectively.

Similar findings were reported by (Anusha *et al.*, 2021 [5]; Panchal *et al.*, 2019 [6]; Awad-Allah *et al.*, 2016 [7]; Santha *et. al.*, 2017 [8]; Bassuony and Sherbiny, 2021 [9]; Hussein, 2021 [10]; Chaudhari, 2014 [11]; Islam *et al.*, 2022 [12]; Azad *et al.*, 2022 [13] and Modarresi *et al.*, 2024 [14]).

Interestingly, high mean performance of parents did not always correspond with good GCA values for traits such as grain yield and zinc content. This indicates that per se performance alone cannot reliably predict the combining ability of parents in hybrid development. Moreover, high SCA effects were not always derived from parents with superior GCA, suggesting the role of both intra- and inter-allelic interactions. Hybrids exhibiting high SCA generally showed higher heterosis, but in some cases, this was associated with average or even poor GCA in one of the parents. This underlines the importance of non-additive gene action in trait expression.

The best performing hybrids for grain yield (Table 6) included IET 31027 x NVSR 1260 (average x good), IET 31004 x DRR Dhan 45 (average x good), IET 31031 x DRR Dhan 45 (average x average), IET 31027 x DRR Dhan 49 (average x average), and IET 31027 x GNR 7 (average x average). These crosses combined high per se performance, positive SCA effects, and heterosis over both the better parent and standard check. For zinc content (Table 7), hybrids such as IET 31027 x GR 23, IET 31027 x DRR Dhan 48, IET 31004 x GR 23, IET 31027 x GR 15, and IET 31031 x GNR 7 recorded significant heterotic response and favourable SCA effects. Notably, the crosses IET 31027 x NVSR 1260, IET 31027 x GR 15, IET 31027 x GNR 7, IET 31031 x GNR 7, and IET 31004 x GR 15 were promising for the simultaneous improvement of both grain yield and zinc content (Table 8).

Overall, hybrids with high SCA effects and at least one parent with good GCA are more likely to produce transgressive segregants in segregating generations. Such crosses could be advanced in breeding pipelines to identify superior recombinants for varietal development. However, since the experiment was conducted at a single location for one season, genotype x environment interaction could have influenced the variance estimates, as noted by Allard and Bradshaw (1964) [15]. Therefore, testing across multiple environments is recommended for reliable conclusions about combining ability and gene action.

Table 3: Summary of general combining ability effect of the parents for 12 characters in rice

Sr. No	Parents	Days to 50 percent flowering	Plant height	Panicle length	Effective tillers per plant	Grains per panicle	L/B ratio
				Lines			
1	IET 31004	A	A	A	A	A	G
2	IET 31027	A	A	A	A	G	P
3	IET 31031	A	A	A	A	P	A
				Testers			
1	DRR Dhan 45	G	A	A	G	G	P
2	GR 15	A	A	A	P	P	A
3	DRR Dhan 48	A	A	A	P	P	G
4	DRR Dhan 49	P	A	A	A	A	G
5	NVSR 1260	A	P	G	G	G	G
6	GR 23	A	A	A	P	A	P
7	GNR 2	A	A	P	A	P	P
8	GNR 7	G	A	A	A	P	A

G = Good general combiner having significant GCA effect in desired direction
A = Average general combiner having either positive or negative but non-significant effects
P = Poor general combiner having significant GCA effect in undesired direction

Table 4: General combining ability effect of parents for different characters in rice

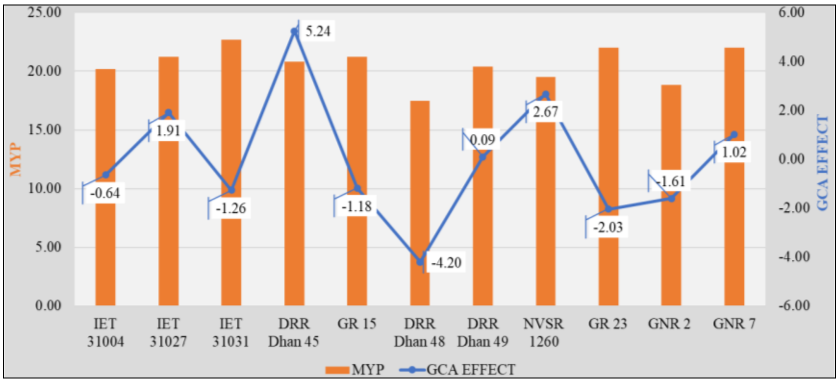
Parents	Days to 50 percent flowering	Plant height	Panicle length	Effective tillers per plant	Grains per panicle	L/B ratio
			Lines			
IET 31004	-	-	0.01	-0.33	-1.44	0.24**
IET 31027	-	-	-0.91	0.48	19.05**	-0.13*
IET 31031	-	-	0.90	-0.15	-17.61	-0.11
$S.E._{gi}$	-	-	0.55	0.19	4.10	0.03
			Testers			
DRR Dhan 45	-4.68**	6.09	0.85	0.79*	60.62**	-0.23**
GR 15	0.60	2.49	-0.37	-1.03**	-32.30**	-0.10
DRR Dhan 48	1.50	-5.87	1.21	-1.34**	-22.60**	0.25**
DRR Dhan 49	3.11**	-0.91	0.08	0.13	-6.92	0.23**
NVSR 1260	0.83	10.67*	2.24*	1.85**	42.92**	0.35**
GR 23	0.75	-0.81	-0.52	-0.65*	-4.90	-0.28**
GNR 2	1.13	-5.89	-2.45**	0.17	-19.11**	-0.31**
GNR 7	-3.25**	-5.77	-1.02	0.09	-17.72*	0.10
$S.E._{gj}$	1.15	4.69	0.90	0.31	6.70	0.06

* and ** indicates significance at 5% and 1% levels of probability, respectively.

Table 4: Continue…

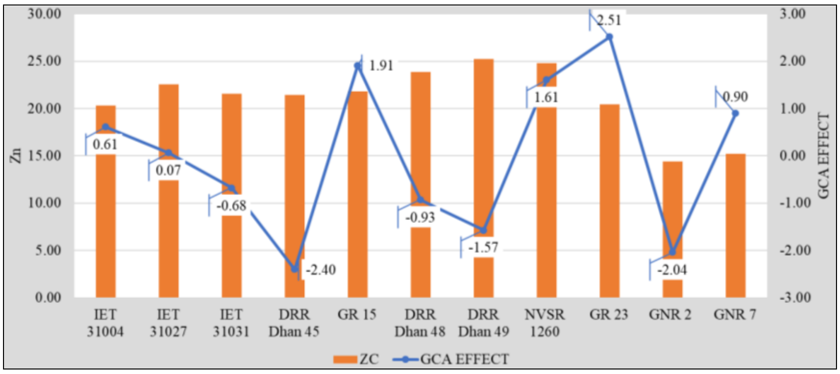
Parents	Grain yield per plant	Straw yield per plant	Test weight	Zn content	Protein content	Amylose content
Lines						
IET 31004	-0.64	-0.88	0.24	0.61	-0.09	0.73
IET 31027	1.91	-1.74	0.58	0.07	-0.11	-0.17
IET 31031	-1.26	2.62	-0.82	-0.68	0.19	-0.56
S.E.gi	0.74	0.90	0.23	0.29	0.10	0.32
Testers						
DRR Dhan 45	5.24**	4.12**	1.40**	-2.41**	-0.29	-1.14*
GR 15	-1.18	-1.20	-0.87*	1.91**	0.36*	0.93
DRR Dhan 48	-4.20**	-5.65**	-2.61**	-0.93	-0.51**	0.89
DRR Dhan 49	0.09	1.01	0.99*	-1.57**	-0.07	0.06
NVSR 1260	2.67*	1.58	1.06**	1.61**	-0.42*	-0.36
GR 23	-2.03	0.74	0.57	2.51**	0.56**	-0.21
GNR 2	-1.60	4.85**	-0.22	-2.04**	-0.03	0.11
GNR 7	1.02	-5.45**	0.32	0.90	-0.41*	-0.28
S.E.gj	1.21	1.46	0.37	0.48	0.17	0.53

* and ** indicates significance at 5% and 1% levels of probability, respectively.



MYP: Mean yield per plant
GCA: General combining ability

Fig 2: Mean values and GCA effects of parents for grain yield per plant (g) in rice



Zn: Zinc content (ppm)
GCA: General combining ability

Fig 3: Mean values and GCA effects of parents for zinc content (ppm) in rice

Table 5: Specific combining ability effect of crosses for different characters in rice

Crosses	Days to 50 percent flowering	Plant height	Panicle length	Effective tillers per plant	Grains per panicle	L/B ratio
IET 31004 x DRR Dhan 45	0.14	-	0.95	2.33**	35.51**	-0.49**
IET 31004 x GR 15	-0.38	-	0.63	0.82	28.65*	-0.21*
IET 31004 x DRR Dhan 48	-2.28	-	-2.81	0.46	13.72	-0.02
IET 31004 x DRR Dhan 49	4.11*	-	1.52	0.80	-45.56**	-0.28*
IET 31004 x NVSR 1260	3.72	-	-0.74	-0.69	-23.26*	0.01
IET 31004 x GR 23	4.47*	-	0.42	-1.03	-2.18	0.26*
IET 31004 x GNR 2	-1.25	-	0.02	-1.32*	15.27	0.53**
IET 31004 x GNR 7	-8.53**	-	0.02	-1.37*	-22.16	0.20
IET 31027 x DRR Dhan 45	1.47	-	-2.23	-2.28	-69.59**	-0.36**
IET 31027 x GR 15	-1.02	-	1.89	0.21	-8.84	0.05
IET 31027 x DRR Dhan 48	3.08	-	-2.49	0.05	-9.61	-0.09
IET 31027 x DRR Dhan 49	-3.64	-	-1.56	-0.42	17.95	0.24
S.E.ij	1.99	-	1.57	0.54	11.60	0.11

* and ** indicates significance at 5% and 1% levels of probability, respectively

Table 5: Continue…

Crosses	Days to 50 percent flowering	Plant height	Panicle length	Effective tillers per plant	Grains per panicle	L/B ratio
IET 31027 x NVSR 1260	-5.26*	-	2.69	0.26	54.51**	-0.04
IET 31027 x GR 23	-2.51	-	0.94	-0.57	-15.51	-0.08
IET 31027 x GNR 2	3.39	-	1.31	2.14**	11.14	-0.25*
IET 31027 x GNR 7	4.49*	-	-0.56	0.62	19.95	0.53**
IET 31031 x DRR Dhan 45	-1.61	-	1.29	-0.05	34.08**	0.85**
IET 31031 x GR 15	1.40	-	-2.52	-1.02	-19.81	0.16
IET 31031 x DRR Dhan 48	-0.79	-	5.30**	-0.51	-4.11	0.11
IET 31031 x DRR Dhan 49	-0.47	-	0.04	-0.38	27.61*	0.03
IET 31031 x NVSR 1260	1.54	-	-1.96	0.43	-31.26**	0.03
IET 31031 x GR 23	-1.95	-	-1.36	1.60**	17.69	-0.18
IET 31031 x GNR 2	-2.14	-	-1.33	-0.82	-26.40*	-0.28*
IET 31031 x GNR 7	4.04*	-	0.54	0.75	2.21	-0.73**
S.E.$_{ij}$	1.99	-	1.57	0.54	11.60	0.11

* and ** indicates significance at 5% and 1% levels of probability, respectively.

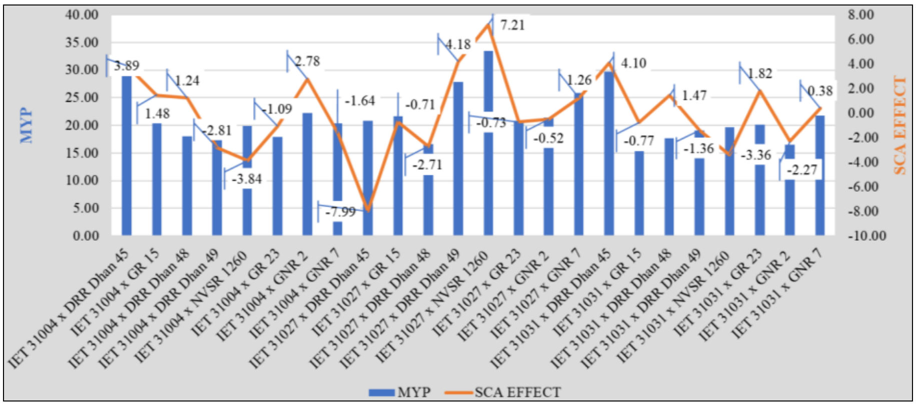
Table 5: Continue…

Crosses	Grain yield per plant	Straw yield per plant	Test weight	Zn content	Protein content	Amylose content
IET 31004 x DRR Dhan 45	3.89	5.13*	2.81**	1.65*	-1.01**	-0.12
IET 31004 x GR 15	1.48	-1.16	-1.00	-1.34	-0.17	1.97*
IET 31004 x DRR Dhan 48	1.24	8.29**	0.32	-1.42	-0.14	-0.59
IET 31004 x DRR Dhan 49	-2.81	3.70	0.66	2.92**	-0.83**	0.81
IET 31004 x NVSR 1260	-3.84	2.03	-3.26**	0.40	0.62*	0.17
IET 31004 x GR 23	-1.09	-1.13	-1.68*	-0.17	1.51**	-0.17
IET 31004 x GNR 2	2.78	-10.14**	-0.85	0.81	-0.19	-0.88
IET 31004 x GNR 7	-1.64	-6.71*	2.99**	-2.85**	0.21	-1.18
IET 31027 x DRR Dhan 45	-7.99**	-13.42**	-0.79	-3.20**	1.20**	0.29
IET 31027 x GR 15	-0.71	2.43	-0.75	0.71	-0.55	-1.03
IET 31027 x DRR Dhan 48	-2.71	0.72	-0.96	4.55**	-0.81**	-0.32
IET 31027 x DRR Dhan 49	4.18	0.49	0.35	-2.03*	0.81**	-1.12
S.E.$_{ij}$	2.09	2.53	0.65	0.83	0.30	0.91

* and ** indicates significance at 5% and 1% levels of probability, respectively.

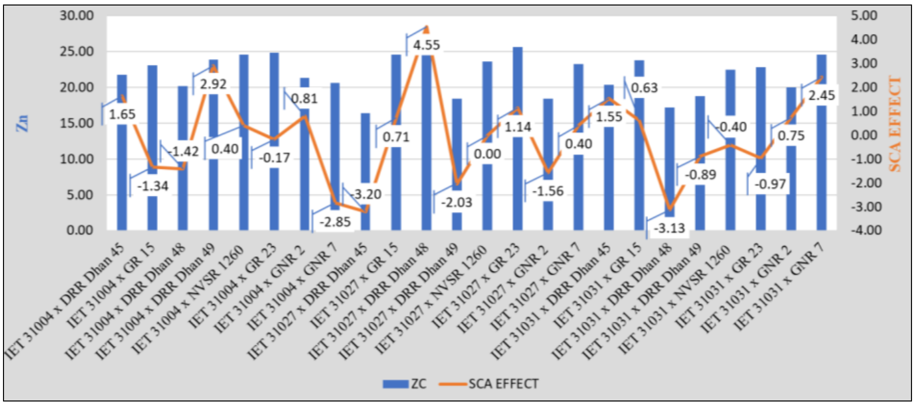
Table 5: Continue…

Crosses	Grain yield per plant	Straw yield per plant	Test weight	Zn content	Protein content	Amylose content
IET 31027 x NVSR 1260	7.21**	4.82	2.88**	0.00	-0.42	-1.21
IET 31027 x GR 23	-0.73	3.13	-1.71*	1.14	-0.62*	0.41
IET 31027 x GNR 2	-0.52	4.85	2.80**	-1.56	0.56	1.00
IET 31027 x GNR 7	1.26	-3.03	-1.81**	0.40	-0.16	1.98*
IET 31031 x DRR Dhan 45	4.10	8.29**	-2.02**	1.55	-0.18	-0.16
IET 31031 x GR 15	-0.77	-1.27	1.75**	0.63	0.72*	-0.94
IET 31031 x DRR Dhan 48	1.47	-9.01**	0.65	-3.13**	0.95**	0.91
IET 31031 x DRR Dhan 49	-1.36	-4.19	-1.01	-0.89	0.02	0.31
IET 31031 x NVSR 1260	-3.36	-6.85**	0.38	-0.40	-0.20	1.04
IET 31031 x GR 23	1.82	-2.00	3.38**	-0.97	-0.89**	-0.24
IET 31031 x GNR 2	-2.27	5.29*	-1.95**	0.75	-0.37	-0.12
IET 31031 x GNR 7	0.38	9.74**	-1.18	2.45**	-0.05	-0.80*
S.E.$_{ij}$	2.09	2.53	0.65	0.83	0.30	0.91



MYP: Mean yield per plant
SCA: Specific combining ability

Fig 4: Mean values and SCA effects for grain yield per plant (g)



Zn: Zinc content (ppm)
SCA: Specific combining ability

Fig 5: Mean values and SCA effects for zinc content (ppm)

Table 6: Top five promising crosses on the basis of *per se* performance for grain yield per plant

Best crosses (P1 x P2)	M.Y.P (g)	GCA Effects		SCA Effects	Zn (ppm)	Significant standard heterosis of other traits in desired direction
		P1	P2			
IET 31027 x NVSR 1260 (average x good)	33.45	1.91	2.67*	7.21**	23.61	DFF, ET, GPP, TW, Zn, PC, AC
IET 31004 x DRR Dhan 45 (average x good)	30.15	-0.64	5.24**	3.89	21.80	DFF, ET, GPP, LB, SYP, TW, PC, AC
IET 31031 x DRR Dhan 45 (average x average)	29.74	-1.26	5.24**	4.10	20.40	DFF, ET, GPP, LB, SYP, TW, PC, AC
IET 31027 x DRR Dhan 49 (average x average)	27.84	1.91	0.09	4.18	18.40	DFF, PL, GPP, Zn, PC, AC
IET 31027 x GNR 7 (average x average)	25.85	1.91	1.02	1.26	23.30	PL, ET, GPP, LB, SYP, TW, PC

Table 7: Top five promising crosses on the basis of *per se* performance for zinc content

Best crosses (P1 x P2)	M.Z.P (ppm)	GCA Effects		SCA Effects	M.Y.P (g)	Significant standard heterosis of other traits in desired direction
		P1	P2			
IET 31027 x GR 23 (average x good)	25.65	0.07	2.51**	1.14	20.81	DFF, GPP, PC, AC
IET 31027 x DRR Dhan 48 (average x average)	25.62	0.07	-0.93	4.55**	16.66	PH, PC, AC
IET 31004 x GR 23 (average x good)	24.89	0.61	2.51**	-0.17	17.90	PC, AC
IET 31027 x GR 15 (average x good)	24.63	0.07	1.91**	0.71	21.68	PC, AC
IET 31031 x GNR 7 (average x average)	24.60	-0.68	0.90	2.45**	21.80	ET, SYP, PC, AC

* and ** indicates significance at 5% and 1% levels of probability, respectively.
M.Z.P = Mean zinc content per plant, M.Y.P(g) = Mean yield per plant DFF = Days to 50 percent flowering, PH = Plant height, ET = Effective tillers per plant, GPP = Grains per panicle, SYP = Straw yield per plant, PC = Protein content, AC = Amylose content

Table 8: Top promising crosses on the basis of *per se* performance for both zinc content and grain yield per plant

Best crosses (P1 x P2)	M.Z.P (ppm)	M.Y.P (g)	Significant standard heterosis of other traits in desired direction
IET 31027 x NVSR 1260	23.61	33.45	DFF, ET, GPP, TW, Zn, PC, AC
IET 31027 x GNR 7	23.30	25.85	PL, ET, GPP, LB, SYP, TW, PC
IET 31031 x GNR 7	24.60	21.80	ET, SYP, PC, AC
IET 31027 x GR 15	24.63	21.68	PC, AC
IET 31004 x GR 15	23.12	21.32	PC

* and ** indicates significance at 5% and 1% levels of probability, respectively.
M.Z.P(g) = Mean zinc content per plant (ppm), M.Y.P(g) = Mean yield per plant (g)
DFF = Days to 50 percent flowering, PH = Plant height, ET = Effective tillers per plant, GPP = Grains per panicle, SYP = Straw yield per plant, Zn = Zinc content, PC = Protein content, AC = Amylose content

References

1. Fukagawa NK, Ziska LH. Rice: importance for global nutrition. J Nutr Sci Vitaminol. 2019;65:S2-S3.
2. Modgil R, Rani U. Effect of processing on the nutritional quality of red rice cultivars. J Life Sci. 2016;8(1-2):12-18.
3. Cakmak I. Enrichment of cereal grains with zinc: agronomic or genetic biofortification? Plant Soil. 2008;302(1):1-17.
4. Swamy BM, Rahman MA, Inabangan-Asilo MA, Amparado A, Manito C, Chadha-Mohanty P, *et al*. Advances in breeding for high grain zinc in rice. Rice. 2016;9(49):1-16.
5. Anusha G, Rao DS, Jaldhani V, Beulah P, Neeraja CN, Gireesh C, *et al*. Grain Fe and Zn content, heterosis, combining ability and its association with grain yield in irrigated and aerobic rice. Sci Rep. 2021;11(1):10579.
6. Panchal R, Bala M, Raval K, Vaghela U. Biochemical evaluation of quality parameters in rice (*Oryza sativa* L.). Int J Curr Microbiol Appl Sci. 2019;8(10):237-244.
7. Awad-Allah MMA, Wissa MT, Elmoghazy AM. Line × tester analysis and heterosis for grain quality characters of some parental lines of hybrid rice (*Oryza sativa* L.). Minufiya J Agric Res. 2016;41(3):567-586.
8. Santha S, Vaithilingam R, Karthikeyan A, Jayaraj T. Combining ability analysis and gene action of grain quality traits in rice (*Oryza sativa* L.) using line × tester analysis. J Appl Nat Sci. 2017;9(2):1236-1255.
9. Bassuony NN, El Sherbiny HA. Line × tester analysis for

grain yield and quality traits in rice (*Oryza sativa* L.). Egypt J Plant Breed. 2021;25(1):25-45.
10. Hussein FA. Heterosis and combining ability of some colored rice genotypes for yield characteristics and grain micronutrient content using line × tester analysis. J Plant Prod. 2021;12(6):635-643.
11. Chaudhari M. Genetic analysis in rice (*Oryza sativa* L.) [MSc thesis]. Navsari (India): N.M. College of Agriculture, Navsari Agricultural University; 2014. 148 p.
12. Islam MZ, Galib MAA, Akand MM, Lipi LF, Akter A, Matin MQI, *et al*. Combining ability and heterotic studies in aromatic rice through line × tester analysis. J Breed Genet. 2022;54(2):221-235.
13. Azad AK, Sarker U, Ercisli S, Assouguem A, Ullah R, Almeer R, *et al*. Evaluation of combining ability and heterosis of popular restorer and male sterile lines for the development of superior rice hybrids. Agronomy. 2022;12(4):965.
14. Modarresi M, AllahGholipour M, Ebadi A. Estimation of gene effects and combining ability for yield and yield components using line × tester analysis in rice (*Oryza sativa* L.). Plant Breed. 2024;29(12):17-29.
15. Allard RW, Bradshaw AD. Implications of genotype-environmental interactions in applied plant breeding. Crop Sci. 1964;4(5):503-508.