



Estimation of heterosis for yield and yield related traits in Rice (*Oryza sativa* L.)

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Abstract

Twenty-four F₁ hybrids generated from Line × Tester mating design along with their eleven parents were tested in a randomized complete block design with three replications. Significantly high magnitude of heterobeltiosis and standard heterosis in desired direction were observed for all the characters except for plant height, kernel length, kernel breadth and L/B ratio. The higher estimates of heterobeltiosis for grain yield per plant were registered by the crosses NDR-359 × IET-32001, IET-31201 × GNR-3 and IET-31078 × NVSR-3777. For grain yield, total three crosses showed significant positive standard heterosis over the standard check for grain yield per plant. The highest standard heterosis for grain yield per plant was registered by the cross IET 31201 × GNR-3, NDR-359 × IET-32001 and IET-31078 × GR-25 (MAHATMA). The crosses recorded significant positive standard heterosis for grain yield per plant were also recorded desirable heterosis for the yield component traits such as productive tillers per plant, grains per panicle, straw yield per plant and 100 grain weight as well as some of the quality traits. Thus, these crosses are promising candidates for further use in heterosis breeding programmes.

Keywords: Heterobeltiosis, standard heterosis, Yield components, L × T mating design

Introduction

Rice (*Oryza sativa* L.) is a self-pollinated member of the family Poaceae with a chromosome number of $2n = 24$. Its florets bear six stamens arranged in a whorl surrounding a centrally positioned pistil. As a primary staple food, rice supports the diet of a large portion of the Asian population (Huang *et al.*, 2012) [13]. The genus *Oryza* comprises 24 species, of which only two—*O. sativa* (Asian rice) and *O. glaberrima* (African rice)—are domesticated. While *O. glaberrima* originated in West Africa, *O. sativa* arose in southern and eastern Asia. Traditionally, *O. sativa* has been categorized into two subspecies, japonica and indica; however, recent genetic analyses indicate that it can be divided into five distinct groups: indica, aus, tropical japonica, temperate japonica, and aromatic (Garris *et al.*, 2005) [12].

During 2023–24, rice was cultivated on 168.36 million hectares worldwide, producing 532.87 million metric tonnes (Anon., 2024a). In India, rice occupied 47.82 million hectares, with a total production of 137.82 million tonnes in the same period (Anon., 2024b) [10]. In Gujarat, rice cultivation covered 1.01 million hectares, achieving a production of 2.61 million tonnes and a productivity of 2850 kg/ha during 2023-24 (Anon., 2024c).

Heterosis refers to the superior performance of F₁ hybrids compared to their parents. It is commonly categorized into heterobeltiosis, mid-parent heterosis, and standard heterosis. Among these, standard heterosis is particularly important when the goal is to develop hybrids that outperform existing high-yielding commercial varieties. For grain yield, positive heterosis is desirable (Alam *et al.*, 2004) [1]. Enhanced grain yield is often associated with favorable heterosis in traits such as the number of filled grains per panicle, total spikelets, and the number of productive tillers per plant (Vanaja and Babu, 2004) [30].

Improving yield productivity is essential for reducing the disparity between production and consumption. Gaining knowledge about heterosis, heritability, and genetic components of a crop equips breeders with the insights needed to design effective breeding strategies for hybrid variety development. The present study aims to evaluate the nature and magnitude of heterosis for grain yield and its associated traits.

Materials and Methods

The present investigation was conducted during the summer and *kharif* (monsoon) seasons of 2024 at the Main Rice Research Centre, NAU, Navsari, Gujarat, using 35 genotypes comprising 3 female lines (IET-31078, NDR-359, and IET-31201), 8 male testers (IET-32001, GNR-3, GR-17, GR-25, NVSR-796, NVSR-4201, NVSR-3930 and NVSR-3777), 24 hybrids developed through a line × tester mating design of Kempthorne (1957) [14]. Tester GR-25 (MAHATMA) was also used as a check variety to calculate standard heterosis. Crosses were made in summer 2024 through hand emasculation in the evening and pollination the following morning, with about 30 spikelets per panicle selected, anthers removed and panicles bagged; pollination with fresh pollen from testers was followed by re-bagging and tagging. Hybrid and parental seeds were harvested and later sown in *kharif* 2024 for the evaluation in Randomized Complete Block Design (RCBD) with three replications. Observations were recorded for fourteen traits viz., days to 50% flowering, plant height (cm), panicle length (cm), productive tillers per plant, grains per panicle, 100-grain weight (g), grain yield per plant (g), straw yield per plant (g), harvest index, kernel length (mm) and breadth (mm), L/B ratio, protein content (%), and amylose content (%). For most of the trait's data was recorded on five randomly selected plants in each plot in every replication whereas, the

data for days to 50% flowering, was collected on a plot basis.

The data for all characters were subjected to standard statistical procedures to calculate mean, variance and heterosis. The significance of heterosis was tested using a t-test.

Result and Discussion

The ANOVA for 14 characters (Table 1) revealed significant genetic variability among the experimental material for most of the studied traits. Significant variation among parents, males, females and hybrids indicates that the material is suitable for heterosis analyses. The significant parent's vs hybrids effects for several yield components and grain quality traits further suggest the presence of exploitable heterosis, making these traits promising targets for hybrid rice improvement. Plant height and harvest index exhibited non-significant genotype effects, indicating relatively limited genetic variability for these characters under the present experimental material. Overall, hybrids varied significantly from their parents, demonstrating the presence of heterosis for most traits.

Heterosis is the F_1 's superiority, which shows increased or decreased performance over better parent value (heterobeltiosis) and standard heterosis (standard check variety). The results obtained from the experimental findings for yield, yield-related traits were computed over

better parents (heterobeltiosis) and for standard heterosis over check (GR-25) are presented in Table 2.

Early flowering is a desirable trait for developing short duration varieties so, negative heterosis for days to 50% flowering is desirable. In the present study, maximum desirable heterobeltiosis was recorded in the cross NDR-359 $\times$ IET-32001 (–8.46%), followed by two other crosses that also expressed significant negative values. With respect to standard heterosis, thirteen crosses exhibited significant negative effects, with the highest desirable heterosis observed in IET-31078 $\times$ NVSR-796 (–14.02%), followed by IET-31078 $\times$ NVSR-4201 (–13.65%) and IET-31078 $\times$ NVSR-3777 (–13.28%). These crosses are promising for developing early-maturing rice varieties. Similar trends were reported by Alvaran *et al.* (2022), Kushal *et al.* (2023), Ramakrishna *et al.* (2023) and Nivedha *et al.* (2024) [2, 17, 21, 24].

Reduction in plant height is a desirable trait in heterosis breeding programmes. In the present study, heterobeltiosis varied from –4.78% (NDR-359 $\times$ GNR-3) to 13.56% (IET-31078 $\times$ NVSR-3930). Standard heterosis over the check variety ranged from –9.49% (IET-31078 $\times$ NVSR-796) to 2.67% (IET-31201 $\times$ NVSR-3777). However, none of the crosses showed significant negative heterosis for relative, heterobeltiosis, or standard heterosis. These findings are in agreement with earlier reports by Sahu *et al.* (2017), El-Mowafi *et al.* (2022) [9, 26] and Ramakrishna *et al.* (2023) [24].

Table 1: Analysis of variance of line $\times$ tester for various characters in rice

Source of variation	Df	Days to 50% flowering	Plant height	Productive tillers per plant	Panicle length	Grains per panicle	Grain yield per plant	Straw yield per plant
Replications	2	13.1	56.37	0.42	0.18	190.11	5.66	20.09
Genotypes	34	43.73**	53.72	2.92**	10.90**	864.47**	67.62**	140.54**
Parents	10	49.33**	61.27	2.94**	12.56**	561.07**	28.42**	48.68**
Males	7	43.76**	43.07	3.48**	11.71**	651.71**	21.60**	57.16*
Females	2	76.33**	132.59	2.37**	17.85**	365.12*	22.31*	2.78
Males vs Females	1	34.37	46.05	0.31	7.96*	318.47	88.44**	81.18**
Hybrids	23	42.26**	52.16	3.03**	9.48**	1015.18**	86.35**	180.59**
Parents vs Hybrids	1	21.33	13.91	0.18	26.76**	432.04*	28.69	138.02**
Error	68	9.05	93.5	0.36	1.56	101.65	8.13	7.97
Replications	2	22.78	0	0.01	0.01	0.14	0.05	2.27
Genotypes	34	11.63	0.96**	0.09**	0.11**	0.14**	1.21**	16.78**
Parents	10	14.08	0.40**	0.05**	0.08**	0.11**	2.20**	10.15**
Males	7	14.04	0.46*	0.03*	0.10**	0.12**	2.69**	11.20**
Females	2	16.87	0.09*	0.05*	0.04	0.01	0.89**	1.65
Males vs Females	1	8.77	0.62	0.01	0.05	0.21**	1.38**	19.77**
Hybrids	23	11.05	1.07**	0.11**	0.12**	0.16**	0.71**	20.09**
Parents vs Hybrids	1	0.34	4.18**	0.31**	0.06*	0.01	2.82**	6.76*
Error	68	7.82	0.09	0.01	0.01	0.02	0.07	1.26

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

Positive heterosis is desirable for productive tillers per plant. Heterobeltiosis varied from –30.14% (NDR-359 $\times$ GR-25) to 33.69% (NDR-359 $\times$ IET-32001), only two cross IET-31201 $\times$ IET-32001 and NDR-359 $\times$ IET-32001 showing significant positive effects. Standard heterosis over the check ranged from –34.75% (IET-31201 $\times$ NVSR-3777) to 10.91% (NDR-359 $\times$ IET-32001), only one cross NDR-359 $\times$ IET-32001 exhibiting significant positive heterosis. Similar trends were reported by Waza *et al.* (2016), Das *et al.* (2017), Premkumar *et al.* (2017), Lingaiah *et al.* (2019), Kumar *et al.* (2020) [7, 16, 18, 23, 31] and Ramakrishna *et al.* (2023) [24].

Longer panicle length is associated with more spikelets and higher grain yield in rice hybrids; hence, positive heterosis

is desirable for panicle length. Heterobeltiosis varied from –28.74% (NDR-359 $\times$ NVSR-4201) to 13.27% (IET-31201 $\times$ NVSR-3777), IET-31201 $\times$ NVSR-3777 is the only cross exhibited significant positive heterobeltiosis for this trait. Standard heterosis ranged from –20.02% (NDR-359 $\times$ NVSR-4201) to 8.10% (IET-31201 $\times$ NVSR-3777), again IET-31201 $\times$ NVSR-3777 being the only cross showing significant positive standard heterosis. This aligns with the results of Begum *et al.* (2020), Neupane (2022), Ramakrishna *et al.* (2023) and Nivedha *et al.* (2024) [6, 20, 21, 24].

Number of grains per panicle is an important yield-contributing component, and in the present study, heterobeltiosis varied from –27.39% (IET-31201 $\times$ GR-25

(MAHATMA)) to 35.74% (NDR-359 × IET-32001), only crosses NDR-359 × IET-32001 and IET-31201 × GNR-3 exhibiting significant positive heterobeltiosis. Standard heterosis ranged from -37.34% (IET-31078 × IET-32001) to 10.13% (IET-31201 × GNR-3), only two crosses *i.e.* IET-31201 × GNR-3 and NDR-359 × IET-32001 recorded significant positive standard heterosis for this trait. These findings are in line with earlier reports by Das *et al.* (2017), Premkumar *et al.* (2017), Begum *et al.* (2020), Neupane (2022), and Shamey *et al.* (2022) [6, 7, 20, 23, 27]. The value of heterobeltiosis ranged from -38.41% (IET-31201 × GR-25 (MAHATMA)) to 42.07% (NDR-359 × IET-32001) for grain yield per plant,

total four crosses expressing significant positive heterobeltiosis among which highest heterobeltiosis was observed in cross NDR-359 × IET-32001 (42.07%) followed by IET-31201 × GNR-3 (30.63%), IET-31078 × NVSR-3777 (22.48%) and IET-31078 × GR-25 (19.95%). Standard heterosis varied from -38.41% to 21.17% and total three hybrids *i.e.* IET-31201 × GNR-3 (21.17%), NDR-359 × IET-32001 (20.79%) and IET-31078 × GR-25 (MAHATMA) (19.95%) recorded significant positive standard heterosis. These findings closely align with earlier reports of Gaballah *et al.* (2021), Alvaran *et al.* (2022), Dodake *et al.* (2022), Shamey *et al.* (2022) [2, 8, 11, 27] and Ramakrishna *et al.* (2023) [24].

Table 2: Per cent heterobeltiosis and standard heterosis for different characters in rice

Crosses	Days to 50 % flowering		Plant height		Productive tillers per plant		Panicle length		Grains per panicle		Grain yield per plant		Straw yield per plant	
	HB	SH	HB	SH	HB	SH	HB	SH	HB	SH	HB	SH	HB	SH
IET-31078 x IET-32001	2.16	-12.92 **	7.03	-5.29	-20.06**	-25.69**	-18.03**	-9.11	-21.79**	-37.34**	-9.08	-24.74**	-0.19	-21.49**
IET-31078 x GNR-3	15.15 **	-1.85	4.74	-7.32	-18.75**	-24.47**	-9.09	-9.11	-18.52**	-28.73**	-13.13	-19.42*	-19.65**	-22.31**
IET-31078 x GR-17 (SARDAR)	3.03	-12.18 **	9.05	-3.5	-25.25**	-30.52**	-3.37	-8.66	-26.17**	-34.98**	-25.03**	-26.52**	-23.77**	-27.73**
IET-31078 x GR-25 (MAHATMA)	4.33	-11.07 **	7.02	-5.3	-14.73**	-14.73**	-2.1	-2.1	-10.14*	-10.14*	19.95**	19.95**	13.08	13.08
IET-31078 x NVSR-796	0.87	-14.02 **	2.28	-9.49	4.39	-2.96	-6.73	-11.84	-11.17	-27.60**	-15.93	-25.39**	-14.07	-24.59**
IET-31078 x NVSR-4201	1.3	-13.65 **	6.16	-6.05	-5.65	-12.29*	-5.29	-10.47	-7.34	-28.24**	-10.84	-21.19**	-10.13	-22.83**
IET-31078 x NVSR-3930	5.63	-9.96 **	13.56	0.5	-22.68**	-28.13**	-7.21	-12.29*	0.3	-23.56**	-5.87	-22.61**	-4.36	-24.59**
IET-31078 x NVSR-3777	1.73	-13.28 **	7.96	-4.46	-3.45	-10.24	-4.76	-9.11	12.25	-19.07**	22.48**	-8.88	10.05	-11.79
NDR-359 x IET-32001	-8.46 **	-12.18 **	2.92	-3.01	33.69**	10.91*	-7.36	3.98	35.74**	9.83*	42.07**	20.79**	46.50**	19.22**
NDR-359 x GNR-3	2.69	-1.48	-4.78	-6.08	-16.13**	-24.47**	-22.27**	-12.75*	-10.92*	-22.08**	-7.96	-14.63	-15.27*	-18.08*
NDR-359 x GR-17 (SARDAR)	-1.54	-5.54 *	-1.76	-9.1	-6.6	-14.73**	-15.86**	-5.55	-12.19*	-22.66**	-6.04	-7.9	-0.09	-5.29
NDR-359 x GR-25 (MAHATMA)	-0.38	-4.43	-4.39	-5.7	-30.14**	-30.14**	-12.15**	-1.39	-18.82**	-18.82**	-18.90*	-18.90*	-14.26*	-14.26*
NDR-359 x NVSR-796	-1.62	-10.33**	-2.53	-5.31	-0.15	-17.16**	-15.38**	-5.02	-3.86	-21.63**	-16.52*	-24.92**	-17.69*	-27.77**
NDR-359 x NVSR-4201	-1.62	-10.33**	1.12	-0.27	1.31	-15.95**	-28.74**	-20.02**	-4.56	-22.77**	-16.27	-25.99**	-17.98*	-29.57**
NDR-359 x NVSR-3930	6.12*	-4.06	6.74	0.72	0.73	-16.43**	-21.05**	-11.38	-2.74	-21.30**	-16.88	-31.66**	-19.49*	-34.22**
NDR-359 x NVSR-3777	10.00**	-2.58	2.74	-2.45	3.59	-14.06*	-22.27**	-12.75*	-5.35	-23.42**	15.01	-13.56	4.13	-15.25*
IET-31201 x IET-32001	1.98	-4.8	7.89	1.68	27.69**	-6.2	-12.30**	-2.75	2.54	-17.85**	-19.53*	-30.61**	-13.02	-26.03**
IET-31201 x GNR-3	1.98	-4.8	0.87	-2.76	7.22	-3.45	7.25	7.23	25.90**	10.13*	30.63**	21.17**	10.8	7.14
IET-31201 x GR-17 (SARDAR)	-0.79	-7.38**	2.25	-5.39	-13.68*	-21.18**	-14.77*	-18.66**	-9.93	-20.68**	-11.99	-13.74	-11.46	-16.06*
IET-31201 x GR-25 (MAHATMA)	-0.79	-7.38**	1.75	-1.91	-23.25**	-23.25**	-13.66*	-13.66*	-27.39**	-27.39**	-38.41**	-38.41**	-36.08**	-36.08**
IET-31201 x NVSR-796	0	-8.86**	3.9	0.17	7.28	-21.20**	0.48	-4.11	-11.21*	-25.51**	-23.61**	-31.30**	-22.12**	-31.66**
IET-31201 x NVSR-4201	7.55*	-1.98	4.16	0.41	-1.46	-27.62**	-2.86	-7.29	-8.81	-23.50**	-30.32**	-38.41**	-23.70**	-34.48**
IET-31201 x NVSR-3930	4.67	-5.37	3.48	-2.36	-3.23	-26.91**	5.71	0.89	-8.87	-23.55**	-25.70**	-35.92**	-23.36**	-34.83**
IET-31201 x NVSR-3777	7.50*	-4.8	8.13	2.67	-18.85**	-34.75**	13.27**	8.10*	-4.82	-20.15**	-14.17	-25.99**	-13.95	-26.82**
S.E. ±	2.46	2.46	7.89	7.89	0.49	0.49	1.02	1.02	8.23	8.23	2.31	2.31	4.17	4.17
IET-31078 x IET-32001	-8.53*	-3.9	-4.76	-8.39*	-9.84**	-13.86**	1.77	6.72	1.35	-16.58**	-33.45**	-10.19*	9.88**	11.53**
IET-31078 x GNR-3	3.48	4.0	-9.63**	-10.16**	3.66	-0.96	-15.02**	-9.06*	-4.18	-11.93**	-11.11**	-10.43**	-23.73**	-22.58**
IET-31078 x GR-17 (SARDAR)	-1.58	2.08	-6.82	-7.62*	1.51	-3.01	-9.62**	-4.74	-11.53**	-16.18**	-10.26**	-0.47	3.03	4.58
IET-31078 x GR-	-4.28	-3.8	-13.79**	-13.79**	-5.66	-5.66	-8.49*	-8.49*	0.91	0.91	2.01	2.01	-5.72	-4.3

25 (MAHATMA)														
IET-31078 x NVSR-796	-3.48	-0.82	1.01	-11.41**	-10.09**	-14.10**	12.30**	3.21	-9.29*	-17.76**	-16.37**	-16.47**	12.09**	13.78**
IET-31078 x NVSR-4201	-0.74	2.15	-3.02	-12.79**	-10.69**	-13.92**	8.41*	1.3	-0.67	-10.11**	2.19	2.07	1.6	3.13
IET-31078 x NVSR-3930	-1.65	-0.9	-5.39	-12.43**	-15.39**	-13.25**	9.97*	1.07	4.94	-9.81**	14.59**	14.45**	-4.42	-2.98
IET-31078 x NVSR-3777	2.88	3.39	-2.88	-11.30**	4.89	0.96	-7.42	-12.12**	8.05	-10.41**	-3.55	4.5	-6.96	-3.35
NDR-359 x IET-32001	-6.16	-1.41	-8.49*	-11.98**	-13.83**	-14.46**	-1.79	2.98	26.19**	7.18*	-24.41**	2.01	-20.99**	-16.48**
NDR-359 x GNR-3	8.99	4.55	-19.67**	-20.15**	-4.85	-5.54	-21.01**	-15.48**	3.3	-5.06	-7.82*	1.95	-22.47**	-18.04**
NDR-359 x GR-17 (SARDAR)	-6.65	-3.18	-12.13**	-12.89**	-0.97	-1.69	-15.90**	-11.35**	-7.04	-11.93**	-8.01*	2.01	10.20**	16.49**
NDR-359 x GR-25 (MAHATMA)	-5.74	-5.74	-4.26	-4.26	-4.1	-4.1	0	0	-14.76**	-14.76**	-19.01**	-10.43**	7.21*	13.34**
NDR-359 x NVSR-796	1.18	3.97	-5.6	-12.75**	-9.83**	-10.48**	5.03	-2.16	-6.77	-15.47**	-7.77*	2.01	-16.14**	-11.35**
NDR-359 x NVSR-4201	2.14	5.11	-3.29	-10.62**	-5.34	-6.02	1.82	-4.86	-10.17*	-18.71**	-5.52	4.5	-12.02**	-6.99
NDR-359 x NVSR-3930	2.97	3.75	-9.80*	-16.52**	-3.53	-1.08	-9.33*	-15.53**	-1.06	-14.96**	-30.21**	-22.81**	-8.37*	-3.13
NDR-359 x NVSR-3777	9.62*	2.04	-1.82	-9.26**	-9.83**	-10.48**	6.84	1.42	0.83	-14.36**	-2.36	8.00*	-0.15	5.55
IET-31201 x IET-32001	-10.68*	-6.16	0	-3.81	-0.26	-8.43**	-0.02	4.84	-8.59*	-21.13**	-24.45**	1.95	12.00**	12.81**
IET-31201 x GNR-3	2.9	4.25	-35.19**	-35.57**	-14.64**	-20.60**	-24.06**	-18.74**	11.77**	2.73	-10.23**	7.05	6.34	6.25
IET-31201 x GR-17 (SARDAR)	-0.81	2.87	-30.43**	-31.03**	-15.75**	-20.72**	-17.43**	-12.96**	-13.98**	-18.50**	-20.22**	-4.86	-1.2	-1.26
IET-31201 x GR-25 (MAHATMA)	-4.8	-3.55	-12.16**	-12.16**	-10.12**	-10.12**	-2.52	-2.24	-14.16**	-14.16**	-18.63**	-2.96	-1.71	-1.79
IET-31201 x NVSR-796	-1.98	0.71	9.78*	-1.23	11.41**	4.7	-5.9	-5.63	-9.78*	-18.20**	-20.62**	-5.33	2.99	2.9
IET-31201 x NVSR-4201	-8.63*	-5.98	-7.97*	-17.20**	-3.75	-7.23*	-10.98**	-10.72**	-5.03	-14.05**	-24.84**	-10.37**	1.44	1.36
IET-31201 x NVSR-3930	-2.66	-1.38	8.33*	0.27	-7.59*	-5.25	5.54	5.85	-2.5	-15.87**	-16.54**	-0.47	-0.51	-0.59
IET-31201 x NVSR-3777	0.06	1.37	-11.57**	-19.24	-15.26**	-18.43**	-1.15	-0.86	0.31	-13.45**	-26.97**	-12.91**	-14.53**	-11.21**
S.E. $\pm$	2.28	2.28	0.25	0.25	0.09	0.09	0.1	0.1	0.12	0.12	0.22	0.22	0.92	0.92

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

Heterobeltiosis for straw yield per plant varied from –36.08% (IET-31201 $\times$ GR-25 (MAHATMA)) to 46.50% (NDR-359 $\times$ IET-32001); NDR-359 $\times$ IET-32001 was the only cross expressing significant positive heterosis for straw yield per plant. Standard heterosis ranged from –36.08% (IET-31201 $\times$ GR-25 (MAHATMA)) to 19.22% (NDR-359 $\times$ IET-32001), NDR-359 $\times$ IET-32001 again being the sole cross showing significant positive heterosis. Similar significant positive heterosis has been reported by Das *et al.* (2017)^[7] and Premkumar *et al.* (2017)^[23].

Positive heterosis is desirable as a high harvest index contributes to greater economic yield. Heterobeltiosis varied from –10.68% (IET-31201 $\times$ IET-32001) to 9.62% (NDR-359 $\times$ NVSR-3777), where NDR-359 $\times$ NVSR-3777 (9.62%) was the only cross exhibiting favourable significant heterobeltiosis. Standard heterosis ranged from –6.16% (IET-31201 $\times$ IET-32001) to 5.11% (NDR-359 $\times$ NVSR-4201), none of the crosses showed significant positive standard heterosis for this trait. These findings align with the reports of Thorat *et al.* (2017) and Kushal *et al.* (2023)^[17, 29].

Heterobeltiosis varied from –35.19% (IET-31201 $\times$ GNR-3) to 9.78% (IET-31201 $\times$ NVSR-796); only two hybrids exhibited significant positive heterobeltiosis for kernel length trait. Standard heterosis ranged from –35.57% (IET-31201 $\times$ GNR-3) to 0.27% (IET-31201 $\times$ NVSR-3930); none of the crosses showing significant positive standard

heterosis for the same. These findings are consistent with those reported by Sharma and Jaiswal (2020) and Meena *et al.* (2021)^[19, 28].

Heterobeltiosis for kernel breadth varied from –15.75% (IET-31201 $\times$ GR-17 (SARDAR)) to 11.41% (IET-31201 $\times$ NVSR-796); IET-31201 $\times$ NVSR-796 was the only cross exhibiting significant positive heterobeltiosis. Economic heterosis ranged from –20.72% (IET-31201 $\times$ GR-17 (SARDAR)) to 4.70% (IET-31201 $\times$ NVSR-796) while, none of the crosses showing significant positive standard heterosis. Similar results were reported by Sharma and Jaiswal (2020) and Meena *et al.* (2021)^[19, 28].

The L/B ratio is an important trait contributing to seed quality. Heterobeltiosis varied from –24.06% (IET-31201 $\times$ GNR-3) to 12.30% (IET-31078 $\times$ NVSR-796). Total three crosses IET-31078 $\times$ NVSR-796 (12.30%), IET-31078 $\times$ NVSR-3930 (9.97%) and IET-31078 $\times$ NVSR-4201 (8.41%) exhibited significant positive heterobeltiosis for the trait. Standard heterosis ranged from –18.74% (IET-31201 $\times$ GNR-3) to 6.72% (IET-31078 $\times$ IET-32001). Similar findings were reported by Roy *et al.* (2019) and Sharma and Jaiswal (2020)^[25, 28] for this trait.

Hundred-grain weight is desirable in the positive direction as heavier seeds contribute to higher yield. Heterobeltiosis ranged from –14.76% (NDR-359 $\times$ GR-25 (MAHATMA)) to 26.19% (NDR-359 $\times$ IET-32001), where NDR-359 $\times$ IET-32001 exhibited the highest favourable heterobeltiosis

followed by IET-31201 × GNR-3 (11.77%). Standard heterosis ranged from -21.13% (IET-31201 × IET-32001) to 7.18% (NDR-359 × IET-32001); NDR-359 × IET-32001 was the only hybrid showing significant positive standard heterosis. These findings align with earlier reports by Gaballah *et al.* (2021), Alvaran *et al.* (2022) and Nivedha *et al.* (2024) [2, 11, 21].

In rice, protein content is an important quality trait determining the nutritional value of the produce. Heterobeltiosis for protein content varied from -33.45% (IET-31078 × IET-32001) to 14.59% (IET-31078 × NVSR-3930); cross IET-31078 × NVSR-3930 being the only cross exhibiting significant positive heterobeltiosis. Standard heterosis ranged from -22.81% (NDR-359 × NVSR-3930) to 14.45% (IET-31078 × NVSR-3930), total two hybrids IET-31078 × NVSR-3930 (14.45%) and NDR-359 × NVSR-3777 (8.00%) showed significant positive standard heterosis for protein content. Comparable results for this trait were also reported by Patil *et al.* (2012) and Kiruba *et al.* (2023) [15, 22].

Heterobeltiosis for amylose content varied from -23.73% (IET-31078 × GNR-3) to 12.09% (IET-31078 × NVSR-796), total five crosses showed significant positive heterobeltiosis. Standard heterosis ranged from -22.58% (IET-31078 × GNR-3) to 16.49% (NDR-359 × GR-17 (SARDAR)), total five crosses expressing significant positive standard heterosis; the highest values were observed in NDR-359 × GR-17 (SARDAR) (16.49%), IET-31078 × NVSR-796 (13.78%) and NDR-359 × GR-25 (MAHATMA) (13.34%). Similar results were reported by Patil *et al.* (2012), Roy *et al.* (2019) and El-Naem *et al.* (2024) [10, 22, 25].

Overall based on the study, the crosses IET-31201 × GNR-3, NDR-359 × IET-32001 and IET-31078 × GR-25 (MAHATMA) showed significant positive heterosis over the standard check GR-25 (MAHATMA) for grain yield per plant as well as yield component traits such as productive tillers per plant, grains per panicle, straw yield per plant and 100 grain weight as well as some of the quality traits. These crosses are promising candidates for further use in heterosis breeding programmes, as they exhibit significant heterobeltiosis and standard heterosis in the desirable direction for grain yield enhancement.

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