E-ISSN: 2618-0618
P-ISSN: 2618-060X

NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; 8(12): 897-903
Received: 26-09-2025
Accepted: 29-10-2025

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Genetic basis of heterosis for grain yield and salinity tolerant traits in rice through diallel analysis

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DOI: https://www.doi.org/10.33545/2618060X.2025.v8.i12m.4513

Abstract
The present study was undertaken using a half diallel mating design in rice to evaluate the *per se* performance of parents and hybrids, along with the extent of heterosis (both heterobeltiosis and standard heterosis) for twelve traits, including grain yield per plant and salinity tolerant traits. The experimental material comprised eight genetically diverse parents and their twenty-eight F_1 hybrids (excluding reciprocals). Significant genetic variability was observed across all traits. Notable levels of heterobeltiosis and standard heterosis were recorded for most characters. On the basis of *per se* performance, parents TNR 1, NVSR 6531 and IR 55179 and hybrids GNR 3 × GR 19, NVSR 6526 × GR 19, NVSR 6531 × GR 19, GR 17 × GR 19 and NVSR 6531 × CSR 103-10-2 exhibited the maximum grain yield per plant. The highest standard heterosis for grain yield was observed in GNR 3 × GR 19 followed by NVSR 6526 × GR 19, NVSR 6531 × GR 19, GR 17 × GR 19 and NVSR 6531 × CSR 103-10-2, while the top heterobeltiosis values were recorded in GNR 3 × GR 19, NVSR 6526 × GR 19, GR 17 × GR 19, GNR 3 × CSR 103-10 2 and NVSR 6531 × GR 19. These promising hybrids also showed high heterosis for key yield-contributing traits such as panicle length, effective tillers per plant, grains per panicle and 100-grain weight, indicating the cumulative effect of these traits in enhancing grain yield.

Keywords: Diallel, heterosis, rice, heterobeltiosis, standard heterosis

Introduction

Rice (*Oryza sativa* L.) a member of the Poaceae family, is a self-pollinating crop with a diploid chromosome number of 2n=24. Its floral structure consists of six stamens arranged in a circular pattern around a central pistil. As a staple food, rice is essential for the diet of most people in Asia. The Oryza genus includes 24 species, of which only two are domesticated: *O. sativa* (Asian rice) and *O. glaberrima* (African rice). While African rice is native to western Africa, Asian rice originated in southern and eastern Asia. Traditionally, *O. sativa* has been divided into two subspecies: *japonica* and *indica*. However, recent genetic research has identified five distinct groups within species: *indica*, *aus*, *tropical japonica*, *temperate japonica* and *aromatic* (Garris *et al.*, 2005) [1]. Rice is cultivated across a wide array of environments, including irrigated fields, rainfed lowlands, uplands and flood prone areas. Asia referred to as the "rice bowl" of the world accounts for over 90 per cent of global rice production and consumption (Tyagi *et al.*, 2004) [2]. Rice kernels are naturally free of cholesterol and sodium, making them an important source of calories worldwide. One cup (186 g) of cooked rice provides approximately 218 calories, 4.5 g protein, 45.8 g carbohydrates, 3.5 g fiber and 1.6 g fat. Rice also supplies essential nutrients like iron, manganese, magnesium and B vitamins (Cervoni, 2024) [3].

Globally, during 2024-25, rice was grown on 168.36 million hectares, producing 532.87 million metric tonnes (Anon., 2025a) [4]. In India, third advance estimates projected production at 119.93 million tonnes (Anon., 2025b) [5]. In Gujarat, rice covered 0.88625 million hectares, yielding 2.13 million tonnes at a productivity rate of 2403.27 kg ha^{-1} (Anon., 2025c) [6]. India has the largest area under rice cultivation, while China remains the top producer. In India, rice is a staple for nearly 65 per cent of the population, contributing approximately 42 per cent to total food grain production and 45 per cent to cereal output. This critical crop supports a large portion of the global population and also serves as a major employment source, especially in developing nations (Muthayya *et al*., 2014) [7].

Nearly 3.7 billion people globally depend on rice. Yet, rapid population growth, deteriorating soil fertility and limited quality irrigation water are driving cultivation into marginal areas increasingly affected by abiotic stress. In India, around 11 per cent of land suffers from salinity, with 1.5 million hectares of irrigated land salinized each year (Gregorio *et al*., 2003) [8]. Soil salinity is a major environmental constraint to agriculture, leading to widespread land degradation in coastal and inland regions. This presents a significant challenge to food security and sustainable farming. Improving the salt tolerance of major crops is one of the most practical strategies to utilize underexploited salt affected areas. Despite extensive research on salinity, only limited success has been achieved in developing salt tolerant varieties for farmers. Given rice's status as a staple crop, breeding salt tolerant cultivars is essential for enhancing global food security. However, salinity tolerance in rice is a complex trait, regulated by multiple physiological and biochemical factors. Thus, there is a need for ongoing research and the development of high yielding varieties for saline environments (Singh *et al*., 2008) [9].

Heterosis in rice was first reported in 1926 and was commercially exploited in China. It remains a powerful tool for enhancing yield and agronomic traits. Parent selection is crucial in this process. Earlier, selection was based on general performance, but now combining ability analysis is preferred. It helps not only in selecting parents but also in understanding gene actions controlling trait expression, enabling breeders to design efficient programs for quick genetic gains.

Diallel cross analysis is a robust and comprehensive genetic breeding methodology that offers valuable insights into the genetic architecture of rice breeding populations. By systematically analysing genetic components, inheritance patterns and the combining abilities of parental lines, this technique allows breeders to identify superior genetic combinations and formulate efficient breeding strategies. A major advantage of diallel analysis is its capacity to simultaneously evaluate genetic variance, types of gene action and hybrid potential within a single generation. This integrated approach provides a holistic understanding of quantitative trait inheritance and supports the strategic selection of parental lines with high genetic potential for the development of superior rice cultivars. Such knowledge is particularly significant for devising targeted breeding strategies aimed at enhancing crop performance in coastal and salt affected soils, thereby improving rice's adaptability and tolerance to salinity.

Materials and Methods

Experimental site

The current study was conducted at the Coastal Soil Salinity Research Station farm at Navsari Agricultural University in Danti, Umbharat, during the *Kharif* season of 2024-25.

Plant materials

The experimental material comprised Eight genotypes (TNR-1, GNR-3, GR-17, IR-55179, NVSR-6531, NVSR-6526, GR-19 and CSR 103 10 2), which were crossed using 8 × 8 Half diallel mating design. The experimental evaluation included 28 F_1 hybrids derived from the crosses, along with their eight parental genotypes and Standard check GR-19 (P_7).

Layout

The experiment was conducted using a Randomized Block Design (RBD) with three replications. Each plot representing the parents and F_1 hybrids consisted of a single row comprising 14 plants. A spacing of 20 × 15 cm was maintained for raising the crop. Observations were recorded from five randomly selected plants in each plot. All recommended agronomic practices were followed to ensure the growth of a healthy and uniform crop stand.

Studied traits

Data were recorded for a range of morphological, physiological and yield-related traits to assess the performance of the genotypes and their hybrids. The traits evaluated included days to 50% flowering, plant height (cm), panicle length (cm), number of effective tillers per plant, number of grains per panicle, L/B ratio, grain yield per plant (g), straw yield per plant (g), 100-grain weight (g), K^+/Na^+ ratio in the shoot, proline content (µg g^{-1} FW) and chlorophyll fluorescence.

Data analysis

Analysis of Variance for Experimental Design

The statistical techniques described by Snedecor and Cochran (1967) and subsequently developed by Panse and Sukhatme (1978) [10] were used to examine the data gathered for each attribute in both parental and hybrid lines. An analysis of variance (ANOVA) was performed for the experimental setting using a Randomised Block Design (RBD). Using a fixed-effect model for the study, this method was utilised to determine the significance of genotype differences for all evaluated attributes.

Estimation of Heterosis

It is thought to be more useful and significant to evaluate heterosis in relation to the superior parent and the standard check. Thus, two important criteria were used in this study to assess heterosis: heterosis over the better parent (Heterobeltiosis), as suggested by Fonseca and Patterson (1968) [11], and heterosis over the standard check (Standard heterosis), as described by Meredith and Bridge (1972) [12]. Following are the formulae used to calculate these parameters as well as the significance tests for them.

$$\text{Heterobeltiosis (\%)} = \frac{\overline{F_1}-\overline{BP}}{\overline{BP}} \times 100$$

$$\text{Standard heterosis (\%)} = \frac{\overline{F_1}-\overline{SC}}{\overline{SC}} \times 100$$

Where,

$\overline{F_1}$ = Mean performance of F1

$\overline{BP}$ = Mean value of better parent of respective cross combination

$\overline{SC}$ = Mean performance of standard check hybrid (GR-19)

Results and Discussion

Analysis of Variance

The analysis of variance (ANOVA) conducted to assess differences between parents and hybrids across 12 traits is summarized in Table 1. The findings showed statistically significant mean squares for genotypes in all examined traits, suggesting substantial genetic variability among the selected genotypes.

The analysis of variance revealed significant differences among the genotypes for all studied traits, confirming the presence of substantial genetic variability. Parents showed high significance for most traits, while hybrids exhibited strong significance for all characters except chlorophyll fluorescence, indicating considerable variation within hybrid combinations. The significant differences observed between parents and hybrids for most traits further demonstrated the expression of heterosis, particularly for grain yield per plant and its related components. Overall, the results confirm that the genetic materials used in this study possessed sufficient diversity to support meaningful selection and improvement.

Table 1: Analysis of variance (mean sum of squares) for yield and its component traits in rice

Source	d.f.	Days to 50% flowering	Plant Height (cm)	Panicle Length (cm)	Effective tiller per plant	Grains per panicle	L/B ratio
Replications	02	1.03	65.97	1.29	2.81	5.02	0.01
Genotypes	35	36.96 **	531.21 **	12.07 **	47.74 **	2266.87 **	0.24 **
Parents	07	53.52 **	648.19 **	3.39	7.38 **	1309.76 **	0.42 **
Hybrids	27	31.51 **	516.25 **	12.54 **	51.29 **	2439.31 **	0.21 **
Parents vs. Hybrids	01	68.15 *	116.44	60.4 **	234.3 **	4310.72 **	0.01
Error	70	11.80	73.12	1.944	1.859	31.79	0.008
Source	**d.f.**	**Grain yield per plant (g)**	**Straw yield per plant (g)**	**100 seed weight**	**K^+/ Na^+ ratio in shoot**	**Proline Content**	**Chlorophyll Fluorescence**
Replications	02	1.81	1.28	0.01	0.28 **	83.73	0.014**
Genotypes	35	234.58 **	699.6 **	0.31 **	1.69 **	9473.98 **	0.005**
Parents	07	42.75 **	231.57 **	0.5 **	1.36 **	5376.67 **	0.008**
Hybrids	27	211.84 **	801 **	0.26 **	1.84 **	5854.93 **	0.004*
Parents vs. Hybrids	01	2191.45 **	1238.08 **	0.14 *	0.02 *	135869.52 **	0.005
Error	70	12.64	6.675	0.029	0.004	49.70	0.002

*, ** Significant at P = 0.05 and P = 0.01 levels of probability, respectively

Mean performance

For any new hybrids to be acceptable, mean performance will be the foremost criteria for selecting the genotypes. The data on mean performance of parents and hybrids along with range for different characters are presented in Table 2.

On the basis of mean performance, parents TNR 1, NVSR 6531 and IR 55179 and hybrids GNR 3 × GR 19, NVSR 6526 × GR 19, NVSR 6531 × GR 19, GR 17 × GR 19 and NVSR 6531 × CSR 103-10-2 exhibited the maximum grain yield per plant. These hybrids were also found to be outstanding in respect of component traits like plant height (cm) panicle length (cm), effective tillers per plant, grains per panicle, straw yield per plant (g), 100-grain weight (g) and proline content. In respect to salinity tolerance, parent GR 19 and hybrid GNR 3 × NVSR 6526 depicted the maximum K^+/ Na^+ ratio in shoot. For proline content and chlorophyll fluorescence, parents IR 55179 and hybrid NVSR 6526 × GR 19 showed excellent performance.

Heterosis

Days to 50 per cent flowering

Early flowering is important for any crop. So, the parent of particular hybrids which flowered earlier was considered as better parent and accordingly heterotic effects were estimated. Heterobeltiosis values ranged between -2.11 per cent (NVSR 6526 × GR 19) to 10.57 per cent (GR 17 × GR 19). Standard heterosis values for days to 50 per cent flowering varied from -5.28 per cent (GR 17 × CSR 103-10-2) to 8.45 per cent (NVSR 6531 × GR 19). No hybrids depicted significant negative heterobeltiosis and standard heterosis for this trait. Similar findings were earlier reported by Singh (2012) [13], Devi *et al.* (2017) [14], Vange *et al.* (2020) [15], Rasheed *et al.* (2021) [16] and Gupta *et al.* (2024) [17].

Plant Height (cm)

Positive heterobeltiosis (HB) and standard heterosis (SH) estimates are desirable for plant height. The values of heterobeltiosis for plant height varied from -32.75 per cent (NVSR 6526 × CSR 103-10-2) to 37.80 per cent (GR 17 × GR 19). Out of all crosses generated, 16 were found significant out, of which 2, were positive. Best significant cross combinations over better parent for plant height were GR 17 × GR 19 (37.80%) and TNR 1 × NVSR 6531 (15.11%). Standard heterosis for plant height ranged between -11.59 per cent (GR 17 × CSR 103-10-2) to 43.21 per cent (TNR 1 × NVSR 6531). Out of 28 hybrids, 10 were significantly positive. The best three hybrid combinations were TNR 1 × NVSR 6531 (43.21%), GR 17 × GR 19 (37.80%) and TNR 1 × GR 17 (32.84%) (Table 3.). The results are in agreement with the findings Rasheed *et al.* (2021) [16], Rahman *et al.* (2022) [18], Salem *et al.* (2022) [19], Gupta *et al.* (2024) [17] and Singh *et al.* (2025) [20] for heterobeltiosis and standard heterosis in negative as well as in positive direction.

Panicle length (cm)

For panicle length, positive values of both better parent heterosis and standard heterosis are desirable. The heterobeltiosis for panicle length among all hybrids varied from -10.68 per cent (IR 55179 × NVSR 6526) to 36.94 per cent (NVSR 6531 × CSR 103-10-2). Out of 28 crosses developed, nine hybrids were significantly positive. The highest better parent heterosis was observed in hybrid NVSR 6531 × CSR 103-10-2 (36.94%), GNR 3 × GR 19 (23.00%) and GNR 3 × NVSR 6531 (15.18%). Standard heterosis for panicle length ranged from -11.50 per cent (GNR 3 × GR 17) to 37.38 per cent (NVSR 6531 × CSR 103-10-2). Out of 28 crosses, 12 crosses were positive. The cross combination NVSR 6531 × CSR 103-10-2 (39.16%) expressed the highest significant positive standard heterosis which was followed NVSR 6526 × GR 19 (23.00%), GNR 3 × GR 19 (23.00%) and TNR 1 × NVSR 6531 (21.41%) (Table 3.). The results are in agreement with Rasheed *et al.* (2021) [16], Rahman *et al.* (2022) [18] and Salem *et al.* (2022) [19].

Effective tillers per plant

Effective tillers per plant is a most important yield contributing trait in rice, hence positive values for both better parent heterosis and standard heterosis are desirable. The estimates of heterobeltiosis for effective tillers per plant varied from -51.59 per cent (GNR 3 × NVSR 6531) to 94.90 per cent (TNR 1 × NVSR 6531). Out of 28 crosses developed, 17 were significant for better parent heterosis, of which 14 were positive. The best three hybrid combinations were TNR 1 × NVSR 6531 (94.90%), NVSR 6531 × CSR 103-10-2 (89.81%) and GNR 3 × GR 19 (88.31%). Standard heterosis for effective tillers per plant varied from -50.65 per cent (GNR 3 × NVSR 6531) to 98.70 per cent (TNR 1 × NVSR 6531). 17 crosses among 28 crosses had significant positive standard heterosis. Among these, three best hybrids with significant positive standard heterosis includes TNR 1 × NVSR 6531 (98.70%) followed by NVSR 6531 × CSR 103-10-2 (93.51%) and GNR 3 × GR 19 (88.31%) (Table 3.). The results are in concordance for heterobeltiosis and standard heterosis with the findings of Shukla *et al*. (2020) [21] and Gupta *et al*. (2024) [17].

Grains per panicle

Significant positive results in better parent heterosis and standard heterosis are desirable for this trait. Results of heterobeltiosis for grains per panicle varied from -34.98 per cent (GR 17 × CSR 103-10-2) to 71.58 per cent (GR 17 × NVSR 6531). Out of 28 crosses, 20 were significant for better parent heterosis in which 10 were positive. The best three hybrid combinations were GR 17 × NVSR 6531 (71.58%), GR 17 × NVSR 6531 (44.00%) and GNR 3 × NVSR 6526 (42.28%). Standard heterosis for grains per panicle varied from -45.22 per cent (GNR 3 × GR 17) to 43.28 per cent (NVSR 6531 × CSR 103-10-2). Out of 28 hybrids developed, 22 revealed significant results out, of which, 7 were positive. Order of hybrids which exhibited the maximum standard heterosis for grains per panicle includes NVSR 6531 × CSR 103-10-2 (43.28%) followed by NVSR 6526 × GR 19 (38.53%) and TNR 1 × NVSR 6531 (37.76%) (Table 3.). The estimates of HB and SH for this trait are in concordance with Rasheed *et al*. (2021) [16], Rahman *et al*. (2022) [18] and Salem *et al*. (2022) [19]. However, Singh *et al*. (2025) [20] reported heterobeltosis in negative direction.

L/B ratio

Positive estimates of heterobeltiosis (HB) and standard heterosis (SH) are desirable for the character L/B ratio. The heterobeltiosis results for L/B ratio varied from -24.36 per cent (IR 55179 × NVSR 6526) to 8.37 per cent (GR 17 × GR 19). Out of 28 crosses, 20 were significant for better parent heterosis, of which, 4 were positive. The hybrid GR 17 × GR 19 (8.37%) recorded the highest estimate of heterobeltiosis followed by NVSR 6531 × GR 19 (6.23%) and NVSR 6526 × CSR 103-10-2 (4.93%). Standard heterosis values for L/B ratio varied from -8.00 per cent (IR 55179 × NVSR 6526) to 27.63 per cent (NVSR 6526 × CSR 103-10-2). Out of 28 hybrids developed, 29 revealed significant results, out of which, 18 were positive. The hybrid NVSR 6526 × CSR 103-10-2 (27.63%) recorded the highest estimate of standard heterosis followed by NVSR 6531 × NVSR 6526 (19.79%) and GR 17 × GR 19 (17.72%) (Table 3.). The results are in agreement with the reports of Ray *et al*. (2021) [22].

Grain yield per plant (g)

The positive heterobeltiosis and standard heterosis is desirable for this character. The heterobeltiosis varied from -46.95 per cent (TNR 1 × IR 55179) to 221.52 per (GNR 3 × GR 19). Out of 28 hybrids, 19 had significant positive heterobeltiosis for this trait. The best three hybrids GNR 3 × GR 19 (221.52%), NVSR 6526 × GR 19 (149.88%) and GR 17 × GR 19 (134.75%) had registered significant heterosis in desirable direction over respective better parent. The standard heterosis varied from -18.64 per cent (TNR 1 × IR 55179) to 221.52 per cent (GNR 3 × GR 19) over check hybrid. Among 28 hybrids, total 18 hybrids exhibited significant positive standard heterosis, of these, the best three hybrid combinations were GNR 3 × GR 19 (221.52%), NVSR 6526 × GR 19 (157.41%) and NVSR 6531 × GR 19 (147.63%) (Table 4.). High level of heterobeltiosis standard heterosis was noticed for grain yield per plant. The findings are in concordance with the reports of Ray *et al*. (2021) [22], Rahman *et al*. (2022) [18], Gupta *et al*. (2024) [17] and Singh *et al*. (2025) [20].

Straw yield per plant (g)

For the character straw yield per plant, positive heterobeltiosis (HB) and standard heterosis (SH) estimates are desirable. The estimates of heterobeltiosis in straw yield per plant varied from -47.29 per cent (GNR 3 × NVSR 6531) to 101.87 per cent (GNR 3 × GR 19). In all, 10 hybrids out of 28 hybrids exhibited significant positive better parent heterosis. The highest better parent heterosis was observed in hybrid GNR 3 × GR 19 (101.87%) followed by TNR 1 × GR 17 (85.11%) and NVSR 6531 × GR 19 (83.02%). Standard heterosis for straw yield per plant ranged from -26.17 per cent (GNR 3 × GR 17) to 192.06 per cent (NVSR 6531 × GR 19). Out of 28 crosses developed, 19 were significantly positive. The cross combination NVSR 6531 × GR 19 (192.06%) expressed the highest significant positive standard heterosis which was followed by TNR 1 × GR 17 (167.29%) and TNR 1 × NVSR 6531 (142.41%) (Table 4.). The results were found in agreement with Ray *et al*. (2021) [22].

100-grain weight (g)

Significant positive results in better parent heterosis and standard heterosis are desirable for the trait. The heterosis over better parent varied from -35.39 per cent (GR 17 × GR 19) to 7.56 per cent (TNR 1 × NVSR 6526). Out of 28 cross combinations, no hybrids depicted significant positive heterobeltiosis for this trait. The standard heterosis ranged from -9.67 per cent (IR 55179 × GR 19) to 37.62 per cent (GNR 3 × GR 17) over check GR 19. Out of 28 hybrids, 13 hybrids exhibited significant positive standard heterosis for this trait. The three best hybrid combinations were GNR 3 × GR 17 (37.62%), GR 17 × NVSR 6526 (36.61%) and GR 17 × IR 55179 (32.39%) (Table 4.). Significant positive estimates of heterosis over better parent and standard check for 100-grain weight were reported by Salem *et al*. (2022) [19], Gupta *et al*. (2024) [17] and Singh *et al*. (2025) [20].

Table 2: Mean values of parents, hybrids and check for different characters

Sr. No	Genotype	DTF	PH	PL	ETPP	GPP	L/B	GYPP	SYPP	100SW	K^+/Na^+	PC	CF
Parents													
1	TNR 1	95.3	128.80	22.80	8.93	122.60	3.966	23.60	41.20	2.59	1.40	137.50	0.805
2	GNR 3	92.3	110.20	19.93	8.27	92.87	3.496	14.24	28.40	3.04	0.75	219.77	0.694
3	GR 17	88.3	98.33	20.47	10.07	77.20	3.743	11.81	25.13	3.48	2.03	215.25	0.703
4	IR 55179	96.7	122.87	20.33	8.40	75.07	3.071	18.30	40.47	2.22	1.50	237.23	0.816
5	NVSR 6531	102.3	124.87	20.20	10.47	86.33	3.792	20.11	45.53	2.69	1.01	222.62	0.807
6	NVSR 6526	95.3	143.73	22.47	12.73	81.67	4.192	15.85	38.40	2.59	2.07	127.88	0.745
7	GR 19	94.67	103.53	20.87	10.27	120.60	3.446	15.39	28.53	2.30	2.87	158.61	0.718
8	CSR 103 10 2	90.7	115.27	20.93	8.07	121.60	4.106	14.36	21.53	2.51	1.91	201.26	0.725

Hybrids													
9	TNR 1 X GNR 3	96.3	127.40	23.47	9.93	100.07	3.812	21.09	39.60	2.77	1.52	85.17	0.708
10	TNR 1 X GR 17	95.3	137.53	21.80	15.93	121.47	3.616	33.20	76.27	2.96	1.30	96.77	0.777
11	TNR 1 X IR 55179	99.3	105.60	21.93	5.27	82.53	3.880	12.52	25.73	2.32	1.05	119.94	0.749
12	TNR 1 X NVSR 6531	97.7	148.27	25.33	20.40	166.13	3.944	32.50	69.17	2.45	1.90	90.84	0.748
13	TNR 1 X NVSR 6526	100.3	108.13	22.13	13.00	91.40	3.866	17.35	38.13	2.79	2.32	14.65	0.773
14	TNR 1 X GR 19	99.7	113.33	22.23	16.80	98.30	3.649	33.78	37.67	2.51	2.96	167.50	0.829
15	TNR 1 X CSR 103 10 2	98.7	113.00	23.60	9.20	114.00	3.785	31.65	54.73	2.59	1.46	31.75	0.798
16	GNR 3 X GR 17	93.7	111.73	18.47	8.47	66.07	3.660	15.83	21.07	3.16	1.11	118.52	0.750
17	GNR 3 X IR 55179	94.7	102.93	19.20	8.73	105.40	3.496	20.08	23.80	2.56	1.58	116.32	0.741
18	GNR 3 X NVSR 6531	97.3	118.53	23.27	5.07	95.40	3.960	20.88	24.00	2.79	2.48	115.87	0.701
19	GNR 3 X NVSR 6526	95.3	109.13	23.47	13.13	132.13	3.572	26.82	36.87	2.52	3.23	144.56	0.781
20	GNR 3 X GR 19	91.7	113.80	25.67	19.33	114.00	3.478	49.47	57.60	2.78	2.93	157.82	0.819
21	GNR 3 X CSR 103 10 2	93.3	110.53	23.47	11.87	134.13	3.542	28.64	40.00	2.87	0.67	122.79	0.759
22	GR 17 X IR 55179	90.3	108.20	21.60	13.00	83.07	3.680	19.78	25.00	3.04	1.20	49.88	0.732
23	GR 17 X NVSR 6531	97.3	111.27	23.27	15.60	148.13	3.415	28.59	41.80	2.35	1.32	95.54	0.773
24	GR 17 X NVSR 6526	93.7	109.87	22.53	9.07	117.60	3.635	25.62	29.73	3.14	1.37	98.98	0.766
25	GR 17 X GR 19	97.7	142.67	22.07	13.60	146.13	4.057	36.12	42.80	2.25	0.87	101.30	0.828
26	GR 17 X CSR 103 10 2	89.7	91.53	20.93	11.47	79.07	3.695	20.77	22.73	2.76	0.72	148.27	0.787
27	IR 55179 X NVSR 6531	98.7	128.73	21.20	15.67	111.33	3.441	28.49	43.60	2.23	1.28	143.61	0.763
28	IR 55179 X NVSR 6526	99.3	114.40	20.07	14.93	87.07	3.170	30.81	39.67	2.14	0.83	28.97	0.733
29	IR 55179 X GR 19	95.7	121.00	21.93	18.80	94.07	3.448	33.58	40.93	2.07	0.78	93.40	0.731
30	IR 55179 X CSR 103 10 2	97.7	114.73	24.00	8.80	123.60	3.453	30.33	45.93	2.46	2.22	155.81	0.780
31	NVSR 6531 X NVSR 6526	101.3	129.00	23.13	11.80	76.10	4.128	19.28	40.73	2.57	2.11	44.49	0.695
32	NVSR 6531 X GR 19	102.7	125.73	23.80	16.07	91.80	4.028	38.10	83.33	2.39	1.68	62.48	0.814
33	NVSR 6531 X CSR 103 10 2	96.3	112.80	28.67	19.87	172.80	3.491	34.18	56.93	2.77	3.16	150.63	0.810
34	NVSR 6526 X GR 19	92.7	120.27	25.67	16.47	167.07	3.676	39.60	57.87	2.56	2.57	184.67	0.829
35	NVSR 6526 X CSR 103 10 2	93.7	96.67	22.80	14.00	110.13	4.398	23.27	29.47	2.58	2.36	104.50	0.763
36	GR 19 X CSR 103 10 2	98.3	99.87	22.67	13.13	119.27	3.598	18.86	25.07	2.16	1.17	86.55	0.751
Mean													
Parents mean		94.46	118.45	21.00	9.65	97.24	3.727	16.71	33.65	2.68	1.69	190.01	0.752
Hybrids mean		96.37	115.95	22.80	13.19	112.44	3.699	27.54	41.79	2.59	1.72	104.70	0.767
General Mean		95.94	116.51	22.40	12.41	109.06	3.705	25.13	39.98	2.61	1.71	123.66	0.764
Range													
Parents	Min.	88.33	98.33	19.93	8.07	75.07	3.07	11.81	21.53	2.22	0.75	127.88	0.694
	Max.	102.33	143.73	22.80	12.73	122.60	4.19	23.60	45.53	3.48	2.87	237.23	0.816
Hybrids	Min.	89.67	91.53	18.47	5.07	66.07	3.17	12.52	21.07	2.07	0.67	14.65	0.695
	Max.	102.67	148.27	28.67	20.40	172.80	4.40	49.47	83.33	3.16	3.23	184.67	0.829
S. E. ±		1.98	4.94	0.80	0.79	3.26	0.05	2.05	1.49	0.10	0.04	4.07	0.03
C.D. at 5%		5.59	13.92	2.27	2.22	9.18	0.14	5.79	4.21	0.28	0.10	11.48	0.08
C.V.%		3.58	7.34	6.22	10.99	5.17	2.37	14.14	6.46	6.47	3.67	5.70	6.38

DTF	=	Days to 50 per cent flowering	GYPP	=	Grain yield per plant (g)
PH	=	Plant height (cm)	SYPP	=	Straw yield per plant (g)
PL	=	Panicle length (cm)	100GW	=	100-grain weight (g)
ETPP	=	Effective tillers per plant	K^+/Na^+	=	K^+/Na^+ ratio in shoot
GPP	=	Grains per panicle	PC	=	Proline content (µg g^{-1}fw)
LB	=	L/B ratio	CF	=	Chlorophyll fluorescence

K^+/Na^+ ratio in shoot

Positive heterobeltiosis and standard heterosis results are desirable for this character. The heterobeltiosis values for K^+/Na^+ ratio in shoot varied from -72.99 per cent (IR 55179 × GR 19) to 145.32 per cent (GNR 3 × NVSR 6531). Out of total crosses, 24 were found significant for better parent heterosis, of which, eight were positive. The hybrid GNR 3 × NVSR 6531 (145.32%) manifested high magnitude of heterobeltiosis followed by NVSR 6531 × CSR 103-10-2 (65.38%) and GNR 3 × NVSR 6526 (56.32%). The estimates of standard heterosis for K^+/Na^+ ratio in shoot varied from -76.49 per cent (GNR 3 × CSR 103-10-2) to 12.64 per cent (GNR 3 × NVSR 6526). Out of 28 hybrids developed, 26 revealed significant results, in which two were positive. Top performing hybrids includes GNR 3 × NVSR 6526 (12.64%) and NVSR 6531 × CSR 103-10-2 (9.93%) (Table 4.). The findings of this character are in concordance with Negm *et al*. (2023) [23].

Proline content (µg g^{-1}fw)

For proline content, heterobeltiosis (HB) and standard heterosis (SH) in positive direction are desirable. Heterobeltiosis for proline content ranged from -89.34 per cent (TNR 1 × NVSR 6526) to 16.43 per cent (NVSR 6526 × GR 19). Out of 28 hybrids, 27 revealed significant results, out of which, only 1 was positive. The hybrid NVSR 6526 × GR 19 (16.43%) recorded the highest and significant positive heterobeltiosis. Standard heterosis for proline content varied from -90.76 per cent (TNR 1 × NVSR 6526) to 16.43 per cent (NVSR 6526 × GR 19). Out of 28 hybrids developed, 23 revealed significant results, out of which, only 1 was positive. The hybrid NVSR 6526 × GR 19 (16.43%) recorded the highest and significant standard heterosis (Table 4.). The results for this character are in agreement with the findings of Negm *et al*. (2023) [23].

Chlorophyll fluorescence

Significant positive results in better parent heterosis and standard heterosis are desirable for the trait. The heterosis over better parent varied from -13.90 per cent (NVSR 6531 × NVSR 6526) to 15.32 per cent (GR 17 × GR 19). Out of 28 hybrids, three hybrids had registered significant positive heterobeltiosis for this trait. The three best hybrid combinations were GR 17 × GR 19 (15.32%), GNR 3 × GR 19 (14.04%) and NVSR 6526 × GR 19 (11.28%). The standard heterosis ranged from -3.27 per cent (NVSR 6531 × NVSR 6526) to 15.46 per cent (TNR 1 × GR 19). Out of 28 hybrids, seven hybrids had registered significant positive standard heterosis for this trait. The three best hybrid combinations were TNR 1 × GR 19 (15.46%), NVSR 6526 × GR 19 (15.37%) and GR 17 × GR 19 (15.32%) (Table 4.). Significant estimates of heterobeltiosis and standard heterosis in both positive and negative direction for chlorophyll fluorescence Patel (2021) [23] and Saini *et al*. (2023) [24].

Table 3: Estimates of heterobeltiosis and standard heterosis in *percent* for Days to 50% flowering, Plant height, Panicle length, Effective tiller per plant, Grain per panicle and L/B ratio

Sr. No	Genotype	DFF		PH		PL		ETPP		GPP		L/B	
		HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)
1	TNR 1 X GNR 3	4.33	1.76	-1.09	23.05 **	2.92	12.46 *	11.19	-3.25	-18.38 **	-17.03 **	-3.88 *	10.62 **
2	TNR 1 X GR 17	7.92 *	0.70	6.78	32.84 **	-4.39	4.47	58.28 **	55.19 **	-0.92	0.72	-8.82 **	4.93 *
3	TNR 1 X IR 55179	4.20	4.93	-18.01 **	2.00	-3.80	5.11	-41.04 **	-48.7 **	-32.68 **	-31.56 **	-2.16	12.6 **
4	TNR 1 X NVSR 6531	2.45	3.17	15.11 **	43.21 **	11.11 *	21.41 **	94.9 **	98.7 **	35.51 **	37.76 **	-0.56	14.44 **
5	TNR 1 X NVSR 6526	5.24	5.99 *	-24.77 **	4.44	-2.92	6.07	2.09	26.62 *	-25.45 **	-24.21 **	-7.77 **	12.18 **
6	TNR 1 X GR 19	5.28	5.28	-12.01 *	9.47	-2.49	6.55	63.64 **	63.64 **	-19.82 **	-18.49 **	-7.99 **	5.89 **
7	TNR 1 X CSR 103 10 2	8.82 **	4.23	-12.27 *	9.14	3.51	13.10 *	2.99	-10.39	-7.01	-5.47	-7.82 **	9.83 **
8	GNR 3 X GR 17	6.04	-1.06	1.39	7.92	-9.77	-11.5 *	-15.89	-17.53	-28.86 **	-45.22 **	-2.22	6.20 **
9	GNR 3 X IR 55179	2.53	0.00	-16.22 **	-0.58	-5.57	-7.99	3.97	-14.94	13.5 **	-12.6 **	-0.02	1.43
10	GNR 3 X NVSR 6531	5.42	2.82	-5.07	14.49 *	15.18 **	11.5 *	-51.59 **	-50.65 **	2.73	-20.9 **	4.43 *	14.91 **
11	GNR 3 X NVSR 6526	3.25	0.70	-24.07 **	5.41	4.45	12.46 *	3.14	27.92 *	42.28 **	9.56 *	-14.77 **	3.66
12	GNR 3 X GR 19	-0.72	-3.17	3.27	9.92	23.00 **	23.00 **	88.31 **	88.31 **	-5.47	-5.47	-0.51	0.93
13	GNR 3 X CSR 103 10 2	2.94	-1.41	-4.11	6.76	12.10 *	12.46 *	43.55 **	15.58	10.31 **	11.22 **	-13.75 **	2.77
14	GR 17 X IR 55179	2.26	-4.58	-11.94 *	4.51	5.54	3.51	29.14 *	26.62 *	7.60	-31.12 **	-1.68	6.80 **
15	GR 17 X NVSR 6531	10.19 **	2.82	-10.89	7.47	13.68 *	11.5 *	49.04 **	51.95 **	71.58 **	22.83 **	-9.95 **	-0.92
16	GR 17 X NVSR 6526	6.04	-1.06	-23.56 **	6.12	0.30	7.99	-28.8 **	-11.69	44.00 **	-2.49	-13.28 **	5.47 *
17	GR 17 X GR 19	10.57 **	3.17	37.8 **	37.8 **	5.75	5.75	32.47 **	32.47 **	21.17 **	21.17 **	8.37 **	17.72 **
18	GR 17 X CSR 103 10 2	1.51	-5.28	-20.59 **	-11.59	0.00	0.32	13.91	11.69	-34.98 **	-34.44 **	-10.01 **	7.23 **
19	IR 55179 X NVSR 6531	2.07	4.23	3.10	24.34 **	4.26	1.60	49.68 **	52.60 **	28.96 **	-7.68 *	-9.25 **	-0.14
20	IR 55179 X NVSR 6526	4.20	4.93	-20.41 **	10.50	-10.68 *	-3.83	17.28	45.45 **	6.61	-27.81 **	-24.36 **	-8.00 **
21	IR 55179 X GR 19	1.06	1.06	-1.52	16.87 *	5.11	5.11	83.12 **	83.12 **	-22.00 **	-22.00 **	0.06	0.06
22	IR 55179 X CSR 103 10 2	7.72 *	3.17	-6.62	10.82	14.65 **	15.02 **	4.76	-14.29	1.64	2.49	-15.91 **	0.19
23	NVSR 6531 X NVSR 6526	6.29 *	7.04 *	-10.25 *	24.6 **	2.97	10.86	-7.33	14.94	-11.85 *	-36.9 **	-1.52	19.79 **
24	NVSR 6531 X GR 19	8.45 **	8.45 **	0.69	21.44 **	14.06 *	14.06 *	53.5 **	56.49 **	-23.88 **	-23.88 **	6.23 **	16.9 **
25	NVSR 6531 X CSR 103 10 2	6.25 *	1.76	-9.66	8.95	36.94 **	37.38 **	89.81 **	93.51 **	42.11 **	43.28 **	-14.99 **	1.29
26	NVSR 6526 X GR 19	-2.11	-2.11	-16.33 **	16.16 *	14.24 **	23.00 **	29.32 **	60.39 **	38.53 **	38.53 **	-12.31 **	6.66 **
27	NVSR 6526 X CSR 103 10 2	3.31	-1.06	-32.75 **	-6.63	1.48	9.27	9.95	36.36 **	-9.43 *	-8.68 *	4.93 **	27.63 **
28	GR 19 X CSR 103 10 2	8.46 **	3.87	-13.36 *	-3.54	8.28	8.63	27.92 *	27.92 *	-1.92	-1.11	-12.37 **	4.42 *
Range	Min.	-2.11	-5.28	-32.75	-11.59	-10.68	-11.50	-51.59	-50.65	-34.98	-45.22	-24.36	-8.00
	Max.	10.57	8.45	37.80	43.21	36.94	37.38	94.90	98.70	71.58	43.28	8.37	27.63

*, ** Significant at P = 0.05 and P = 0.01 levels of probability, respectively
HB: Heterobeltiosis, SH: Standard heterosis

Table 4: Estimates of heterobeltiosis and standard heterosis in *percent* for Grain yield per plant, Straw yield per plant, 100 Grain weight, K^+/Na^+ ratio in shoot, Proline content and Chlorophyll fluorescence

Sr. No	Genotype	GYPP		SYPP		100GW		K^+/Na^+		PC		CF	
		HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)	HB (%)	SH (%)
1	TNR 1 X GNR 3	-10.64	37.06	-3.88	38.79 **	-8.94	20.68 **	8.58 *	-47.17 **	-61.24 **	-46.3 **	-12.07 *	-1.39
2	TNR 1 X GR 17	40.7 **	115.8 **	85.11 **	167.29 **	-14.98 **	28.73 **	-35.63 **	-54.54 **	-55.04 **	-38.99 **	-3.50	8.21
3	TNR 1 X IR 55179	-46.95 **	-18.64	-37.54 **	-9.81	-10.36	0.96	-29.78 **	-63.33 **	-49.44 **	-24.38 **	-8.28	4.26
4	TNR 1 X NVSR 6531	37.74 **	111.26 **	51.90 **	142.41 **	-8.86	6.53	36.05 **	-33.81 **	-59.2 **	-42.73 **	-7.25	4.20
5	TNR 1 X NVSR 6526	-26.48 *	12.76	-7.44	33.64 **	7.56	21.33 **	12.17 **	-19.17 **	-89.34 **	-90.76 **	-4.05	7.60
6	TNR 1 X GR 19	43.16 **	119.57 **	-8.58	32.01 **	-2.82	9.45	3.14	3.14	5.61	5.61	2.96	15.46 **
7	TNR 1 X CSR 103 10 2	34.11 **	105.68 **	32.85 **	91.82 **	0.15	12.80 *	-23.56 **	-49.19 **	-84.23 **	-79.99 **	-0.86	11.18 *
8	GNR 3 X GR 17	11.18	2.90	-25.82 **	-26.17 **	-9.11 *	37.62 **	-45.12 **	-61.25 **	-46.07 **	-25.27 **	6.75	4.43
9	GNR 3 X IR 55179	9.70	30.51	-41.19 **	-16.59 *	-15.96 **	11.36	5.42	-44.94 **	-50.97 **	-26.66 **	-9.20	3.21
10	GNR 3 X NVSR 6531	3.81	35.72	-47.29 **	-15.89 *	-8.31	21.51 **	145.32 **	-13.74 **	-47.95 **	-26.95 **	-13.08 **	-2.35
11	GNR 3 X NVSR 6526	69.22 **	74.32 **	-3.99	29.21 **	-17.35 **	9.53	56.32 **	12.64 **	-34.22 **	-8.85 *	4.89	8.75
12	GNR 3 X GR 19	221.52 **	221.52 **	101.87 **	101.87 **	-8.84	20.81 **	2.09	2.09	-28.19 **	-0.50	14.04 *	14.04 *
13	GNR 3 X CSR 103 10 2	99.47 **	86.13 **	40.85 **	40.19 **	-5.78	24.86 **	-64.63 **	-76.49 **	-44.13 **	-22.58 **	4.67	5.67
14	GR 17 X IR 55179	8.05	28.54	-38.22 **	-12.38	-12.56 **	32.39 **	-40.64 **	-58.08 **	-78.98 **	-68.55 **	-10.39 *	1.87
15	GR 17 X NVSR 6531	42.14 **	85.83 **	-8.20	46.50 **	-32.4 **	2.35	-34.74 **	-53.91 **	-57.08 **	-39.76 **	-4.18	7.64
16	GR 17 X NVSR 6526	61.64 **	66.51 **	-22.57 **	4.21	-9.77 *	36.61 **	-33.94 **	-52.4 **	-54.02 **	-37.6 **	2.84	6.62
17	GR 17 X GR 19	134.75 **	134.75 **	50.00 **	50.00 **	-35.39 **	-2.18	-69.84 **	-69.84 **	-52.94 **	-36.13 **	15.32 **	15.32 **

18	GR 17 X CSR 103 10 2	44.65 *	34.97	-9.55	-20.33 **	-20.62 **	20.20 **	-64.52 **	-74.95 **	-31.12 **	-6.52	8.59	9.62
19	IR 55179 X NVSR 6531	41.62 **	85.15 **	-4.25	52.8 **	-17.09 **	-3.09	-14.41 **	-55.3 **	-39.46 **	-9.46 *	-6.59	6.18
20	IR 55179 X NVSR 6526	68.34 **	100.27 **	-1.98	39.02 **	-17.56 **	-7.01	-59.94 **	-71.14 **	-87.79 **	-81.73 **	-10.27 *	2.00
21	IR 55179 X GR 19	83.44 **	118.24 **	1.15	43.46 **	-9.67	-9.67	-72.99 **	-72.99 **	-60.63 **	-41.11 **	-10.47 *	1.77
22	IR 55179 X CSR 103 10 2	65.69 **	97.12 **	13.51 *	60.98 **	-2.26	6.97	16.59 **	-22.5 **	-34.32 **	-1.77	-4.44	8.63
23	NVSR 6531 X NVSR 6526	-4.15	25.31	-10.54 *	42.76 **	-4.43	11.71	1.87	-26.6 **	-80.01 **	-71.95 **	-13.9 **	-3.27
24	NVSR 6531 X GR 19	89.42 **	147.63 **	83.02 **	192.06 **	-10.84 *	4.22	-41.42 **	-41.42 **	-71.94 **	-60.61 **	0.93	13.39 *
25	NVSR 6531 X CSR 103 10 2	69.93 **	122.15 **	25.04 **	99.53 **	3.20	20.64 **	65.38 **	9.93 **	-32.34 **	-5.03	0.36	12.74 *
26	NVSR 6526 X GR 19	149.88 **	157.41 **	50.69 **	102.8 **	-1.12	11.54	-10.55 **	-10.55 **	16.43 **	16.43 **	11.28 *	15.37 **
27	NVSR 6526 X CSR 103 10 2	46.82 *	51.25 **	-23.26 **	3.27	-0.27	12.50 *	14.00 **	-17.86 **	-48.08 **	-34.11 **	2.53	6.30
28	GR 19 X CSR 103 10 2	22.57	22.57	-12.15	-12.15	-13.99 *	-5.88	-59.09 **	-59.09 **	-57.00 **	-45.43 **	3.52	4.51
Range	Min.	-46.95	-18.64	-47.29	-26.17	-35.39	-9.67	-72.99	-76.49	-89.34	-65.50	-13.90	-3.39
	Max.	221.52	221.52	101.87	192.06	7.56	37.62	145.32	12.64	16.43	11.86	15.32	16.01

*, ** Significant at P = 0.05 and P = 0.01 levels of probability, respectively

HB: Heterobeltiosis, SH: Standard heterosis

Conclusion

Based on overall performance, the parents NVSR 6531, GR 19 and CSR 103-10-2, along with the hybrids NVSR 6526 × GR 19, NVSR 6531 × CSR 103-10-2, GNR 3 × GR 19, TNR 1 × NVSR 6531, GR 17 × GR 19, GNR 3 × NVSR 6526 and TNR 1 × GR 17 were identified as promising. These genotypes can be effectively utilized in future rice breeding programmes for developing high-yielding and salinity-tolerant varieties or hybrids.

Acknowledgement

I gratefully acknowledge and express my sincere gratitude to my research guide, Dr. H. K. Joshi and the esteemed advisory committee for their invaluable guidance, encouragement and constructive suggestions throughout this study. I am thankful to Navsari Agricultural University authorities, faculty members and staff for providing essential facilities and support. I owe my deepest gratitude to my parents, family members, relatives, and friends for their unwavering moral support and encouragement.

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