

Original Research Article

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Combining Ability Analysis for Yield and Morphophysiological Traits in Rice (*Oryza sativa* L.) under Sodic Soil Conditions Using Line $\times$ Tester Design

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ABSTRACT

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Soil sodicity poses a significant challenge to rice (*Oryza sativa* L.) production, especially in the salt-affected regions of India. This study aimed to evaluate the combining ability of rice genotypes for yield and morphophysiological traits under sodic soil conditions using a Line $\times$ Tester mating design. Thirteen diverse lines and four testers were crossed to produce 52 F₁ hybrids, which were evaluated along with their parents under sodic conditions during the Kharif seasons of 2023 and 2024. Significant variation among genotypes was observed for all eleven traits studied, indicating ample genetic diversity. Line $\times$ Tester analysis revealed that specific combining ability (SCA) variance was higher than general combining ability (GCA) variance for most traits, suggesting the predominance of non-additive gene action. Among the parents, lines such as NDRK 5081, NDRK 5012, and NDRK 50030 were identified as good general combiners for grain yield and associated traits, while some genotypes like NDRK 5082 showed poor GCA effects. Testers such as IR 6 and CSR 28 also demonstrated favorable GCA for key traits under sodic conditions. Several hybrids, including NDRK 5081 $\times$ IR 6 and NDRK 5012 $\times$ CSR 28, exhibited high SCA effects for grain yield, plant height, and panicle length, making them promising candidates for hybrid development. The findings highlight the potential of utilizing both additive and non-additive gene actions through the selection of superior parental lines and hybrids for improving rice performance in sodic soils.

Introduction

Rice (*Oryza sativa* L.) is a staple food crop for more than half of the global population and serves as a primary source of calories and livelihood in many Asian and African countries. In India, it contributes significantly to

food security, but its productivity is hampered by various abiotic stresses, among which soil sodicity is particularly detrimental (Minhas and Sharma, 2006). Sodic soils, characterized by high pH, poor soil structure, and excessive exchangeable sodium, adversely affect water and nutrient uptake, plant vigor, and ultimately grain

yield (Yaduvanshi *et al.*, 2014). Approximately 3 million hectares of land in India are affected by sodicity, posing a serious challenge to sustainable rice production (ICAR-CSSRI, 2020).

Genetic improvement through hybrid breeding is a viable strategy to enhance rice productivity under stress conditions, including sodicity. Success in hybrid development largely depends on identifying suitable parental lines based on their combining ability. The Line $\times$ Tester (L $\times$ T) mating design, originally proposed by Kempthorne (1957), is a robust tool to assess the general combining ability (GCA) of parents and the specific combining ability (SCA) of crosses. This approach helps breeders determine the nature of gene action and select superior parents and hybrid combinations for target traits.

Previous studies have demonstrated the utility of combining ability analysis for identifying promising rice genotypes under normal and stress-prone environments (Rashid *et al.*, 2017; Bhowmick *et al.*, 2019). However, limited attention has been given to morphophysiological traits associated with sodicity tolerance in L $\times$ T-based studies. Integrating these traits into breeding programs could enhance the selection efficiency under sodic soil conditions.

The present study aims to evaluate the combining ability of selected rice genotypes for yield and key morphophysiological traits under sodic soil conditions. The findings will provide valuable insights into parent selection and hybrid development for cultivating rice in salt-affected areas.

Material and Methods

Experimental Site and Design

The present investigation entitled “Combining Ability Analysis for Yield and Morphophysiological Traits in Rice (*Oryza sativa* L.) under Sodic Soil Conditions Using Line $\times$ Tester Design” was conducted at the Genetics and Plant Breeding Research Farm, Department of Genetics and Plant Breeding, Acharya Narendra Deva University of Agriculture and Technology (NDUAT), Kumarganj, Ayodhya (Faizabad), Uttar Pradesh, India. The experimental site is located at 26.47°N latitude and 82.12°E longitude with an elevation of 113 meters above sea level. The study was carried out during the Kharif seasons of 2023 and 2024 under sodic soil conditions,

characterized by high exchangeable sodium percentage (ESP >15%), high soil pH (>8.5), and poor physical soil structure.

Experimental Materials

The experimental material consisted of 69 rice genotypes, including 52 F₁ hybrids and 17 parental lines (13 lines and 4 testers), developed using a Line $\times$ Tester mating design as per Kempthorne (1957). The 13 lines were selected based on their genetic diversity and performance under sodic conditions, while the 4 testers were chosen for their contrasting performance and adaptability. Crosses were made during the Kharif season of 2023, and the F₁s along with parents were evaluated during the Kharif season of 2024.

Experimental Layout

The experiment was laid out in a Randomized Block Design (RBD) with three replications. Each genotype (F₁ hybrid or parent) was sown in a plot of two rows, each 3 meters long, with a spacing of 20 cm between rows and 15 cm between plants. Recommended agronomic and plant protection practices were followed uniformly to raise a healthy crop and minimize environmental variability.

Traits Studied

In the present study, eleven quantitative traits were recorded to evaluate the combining ability of rice genotypes under sodic soil conditions. These traits included days to 50% flowering, days to maturity, plant height (cm), number of panicle-bearing tillers per plant, panicle length (cm), number of spikelets per panicle, spikelet fertility percentage, 1000-grain weight (g), biological yield per plant (g), harvest index (%), and grain yield per plant (g). Traits such as days to 50% flowering, days to maturity, and 1000-grain weight were recorded on a plot basis, whereas the remaining traits were measured from five randomly selected competitive plants in each plot and averaged for statistical analysis.

Statistical Analysis

The statistical analysis for combining ability was performed using the Line $\times$ Tester design as described by Kempthorne (1957), which allowed partitioning of variances into General Combining Ability (GCA) and

Specific Combining Ability (SCA) effects. Analysis of variance (ANOVA) was conducted to assess the significance of variation among parents, hybrids, and their interactions. Estimates of GCA for lines and testers and SCA for crosses were calculated to determine the genetic control of traits. The ratio of GCA to SCA variances was used to infer the predominance of additive or non-additive gene action. Statistical analyses were carried out using MS Excel, R software, and the OPSTAT online tool.

Results and Discussion

The analysis of variance (Table 1) revealed significant differences among genotypes for all eleven traits under sodic soil conditions, indicating the presence of substantial genetic variability among the parents and hybrids. The highly significant mean squares due to crosses for all traits confirmed the existence of considerable genetic diversity, which is a prerequisite for effective selection and genetic improvement in rice (Rabbani *et al.*, 2013; Yadav *et al.*, 2021).

Partitioning of the total variance among parents, crosses, and parents vs. crosses showed that both additive and non-additive gene actions played important roles in the inheritance of yield and morphophysiological traits. Significant differences in "Parents vs. Crosses" indicated the presence of heterosis and suggested that hybrids performed differently from their parental genotypes, which aligns with findings reported by Ahmed *et al.*, (2020).

The Line $\times$ Tester analysis showed highly significant mean squares for lines, testers, and line $\times$ tester interactions across all traits, suggesting that both general combining ability (GCA) and specific combining ability (SCA) effects were important. The significant GCA effects observed for grain yield, spikelet fertility, and panicle length indicate that additive gene action is substantial under sodic conditions. These results are consistent with earlier studies in rice under abiotic stress conditions (Patel *et al.*, 2014; Islam *et al.*, 2020).

On the other hand, significant SCA effects for all traits, especially grain yield, harvest index, and spikelets per panicle, revealed the importance of non-additive gene action. In traits where the SCA variance exceeded GCA variance, non-additive genetic control was more prominent. This suggests that hybrid development may be an effective strategy for improving rice performance

under sodic stress. Similar results have been reported in salt-stressed environments (Rashid *et al.*, 2017; Choudhary *et al.*, 2019).

The combining ability variances and genetic components of variance for the 11 traits under sodic soil are presented in Table 2. The variance due to specific combining ability (σ^2_{sca}) was higher than general combining ability (σ^2_{gca}) for most traits, indicating the predominant role of non-additive gene action. Such observations support the findings of Ahmed *et al.*, (2020) and Islam *et al.*, (2020), where non-additive gene effects were found significant under saline and sodic conditions in rice.

The additive (D) and dominance (H) components also reflect the nature of gene action. Dominance variance (H) was higher than additive variance (D) for most traits, suggesting that dominance effects were more influential. This aligns with the reports by Patel *et al.*, (2014) and Rashid *et al.*, (2017), who found that dominance gene action was crucial for yield and yield components under abiotic stress conditions.

The degree of dominance (calculated as $\sqrt{H/D}$) further confirmed the involvement of over-dominance (value >1) for all traits except spikelets per panicle (0.56), spikelet fertility (0.76), and 1000-seed weight (0.51), which showed partial dominance. Traits such as days to maturity (2.09), plant height (1.34), and biological yield (1.18) indicated strong over-dominance, suggesting that exploitation through heterosis breeding would be effective (Choudhary *et al.*, 2019; Yadav *et al.*, 2021).

The per cent contribution of lines, testers, and line $\times$ tester interaction to the total genetic variance further elucidates the genetic control of the traits. Lines contributed more than testers for all traits, especially for grain yield (70.69%), biological yield (63.89%), and harvest index (56.13%), indicating that the choice of suitable female parents is more critical for improving these traits. A substantial contribution of line $\times$ tester interaction (more than 25% for most traits) highlights the importance of specific cross combinations in breeding programs (Rabbani *et al.*, 2013).

The general combining ability (GCA) effects of parents for 11 traits in rice under sodic soil conditions are presented in Table 3. The analysis revealed significant variability among the lines and testers, indicating the predominance of additive gene action in the inheritance of these traits.

Table.1 Analysis of variance for combining ability for 11 traits in rice under sodic soil

Characters	df	Days to 50% flowering	Days to maturity	Plant height (cm)	Panicle bearing tillers per plant	Panicle length (cm)	Spikelets per panicle	Spikelet fertility (%)	1000-seed weight (g)	Biological yield per plant	Harvest index (%)	Grain yield per plant
Replication	2	1.87	11.85	29.51	0.19	0.25	7.45	3.32	0.02	9.96	1.46	1.09
Genotypes	68	14.37**	30.27**	62.84**	1.73**	7.73**	1058.62**	11.75**	6.52**	205.18**	23.25**	12.92**
(i) Parents	16	7.87**	23.8**	31.53*	0.87**	5.56**	856.09**	4.01**	3.05**	168.88**	19.66**	8.54**
(ii) Crosses	51	15.4**	30.79**	68.85**	1.68**	7.42**	1133.93**	14.24**	7.63**	194.21**	23.59**	12.24**
(iii) Parents v/s crosses	1	65.92**	106.91**	257.2**	18.16**	58.35**	458.53*	8.38*	5.27*	1345.4**	62.99**	117.77**
(a) Lines	12	24.01*	49.16*	157.88**	3.41**	12.7**	2654.72**	18.66**	13.59**	527.32**	56.29**	36.77**
(b) Tester	3	38.28*	64.09*	106.15*	5.18**	27.45**	5873.69**	103.97**	49.38**	359.55**	49.33**	14.65*
(c) Line x tester	36	10.62**	21.9**	36.06**	0.82**	3.99**	232.02**	5.29**	2.17*	69.39**	10.55**	3.86**
Error	136	2.98	3.98	15.8	0.18	1.17	82.58	1.46	1.29	8.37	1.38	1.2

*, ** Significant at 5% and 1% probability levels respectively.

Table.2 General and specific combining ability variances, additive (D) and dominance (H) components of genetic variance, degree of dominance and per cent contribution of different components towards total genetic variance for 11 traits in rice under sodic soil

Characters	Days to 50% flowering	Days to maturity	Plant height (cm)	Panicle bearing tillers per plant	Panicle length (cm)	Spikelets per panicle	Spikelet fertility (%)	1000-seed weight (g)	Biological yield per plant	Harvest index (%)	Grain yield per plant
σ^2_{gca}	0.80	1.36	3.76	0.14	0.63	158.12	2.20	1.15	14.67	1.66	0.86
σ^2_{sca}	2.55	5.97	6.75	0.21	0.94	49.81	1.28	0.29	20.34	3.06	0.89
D	3.22	5.45	15.05	0.55	2.52	632.50	8.79	4.60	58.67	6.63	3.43
H	10.19	23.89	27.01	0.85	3.76	199.25	5.11	1.17	81.36	12.23	3.55
H/D	0.32	0.23	0.56	0.64	0.67	3.17	1.72	3.92	0.72	0.54	0.97
Degree of dominance	1.78	2.09	1.34	1.25	1.22	0.56	0.76	0.51	1.18	1.36	1.02
Per cent contribution											
Lines	36.68	37.56	53.96	47.71	40.27	55.09	30.83	41.88	63.89	56.13	70.69
Tester	14.62	12.24	9.07	18.09	21.75	30.47	42.95	38.06	10.89	12.30	7.04
Line x Tester	48.69	50.20	36.97	34.20	37.98	14.44	26.22	20.05	25.22	31.57	22.27

Table.3 General combining ability effects of parents for 11 characters in rice

Parent	Days to 50% flowering	Days to maturity	Plant height (cm)	Panicle bearing tillers per plant	Panicle length (cm)	Spikelets per panicle	Spikelet fertility (%)	1000-seed weight (g)	Biological yield per plant	Harvest index (%)	Grain yield per plant
Testers											
PR 124	-	-	0	-	0	-	-	-	-	+	-
IR 6	+	+	0	+	+	+	+	+	+	-	+
Govind	0	0	0	-	-	-	-	-	-	+	-
IR 26	+	+	-	+	+	+	+	+	+	0	0
Lines											
NDRK 50032	-	-	0	+	+	+	-	+	-	+	-
PSBRC 90	0	0	+	+	+	+	0	0	0	0	0
NDRK 5012	-	0	-	+	+	+	-	-	+	-	+
NDRK 50004	0	0	-	+	+	0	0	+	0	0	0
NDRK 5081	+	-	+	0	0	0	-	0	+	0	+
NDRK 5014	-	0	-	-	0	-	+	+	+	-	+
NDRK 5097	0	0	0	-	0	-	0	-	+	0	+
NDRK 5095	0	0	0	+	-	+	0	-	-	+	-
NDRK 5093	-	-	+	-	0	+	0	0	0	0	0
NDRK 5040	+	0	0	-	0	-	+	0	-	+	-
NDRK 50030	0	+	-	+	-	-	+	-	+	-	+
NDRK 5022	0	+	+	-	-	-	+	0	+	-	+
Getu	+	+	+	0	+	-	0	+	-	+	-

+ = Good combiner (significantly positive effect), - = Poor combiner (significantly negative effect) and 0 = Average combiner (non-significant or near zero effect)

Table.4 The parents exhibiting significant and desirable general combining ability effects for different characters in rice

Character	Parents (Lines and Testers)
Days to 50% flowering	NDRK 50032, NDRK 5012, NDRK 5014, NDRK 5093, PR 124
Days to maturity	NDRK 50032, NDRK 5081, NDRK 5093, PR 124
Plant height (cm)	NDRK 5012, NDRK 50004, NDRK 50030, IR 26
Panicle bearing tillers/plant	NDRK 50032, PSBRC 90, NDRK 5012, NDRK 50004, NDRK 5095, NDRK 50030, IR 6, IR 26
Panicle length (cm)	NDRK 50032, PSBRC 90, NDRK 5012, NDRK 50004, Getu, IR 6, IR 26
Spikelets per panicle	NDRK 50032, PSBRC 90, NDRK 5012, NDRK 5095, IR 6, IR 26
Spikelet fertility (%)	NDRK 5014, NDRK 5022, NDRK 5040, NDRK 50030, IR 6, IR 26
1000-grain weight (g)	NDRK 50032, NDRK 50004, NDRK 5014, NDRK 5081, Getu, IR 6, IR 26
Biological yield per plant	NDRK 5012, NDRK 5014, NDRK 5097, NDRK 50030, NDRK 5022, IR 6
Harvest index (%)	NDRK 50032, NDRK 5095, NDRK 5040, Getu, IR 6
Grain yield per plant (g)	NDRK 5012, NDRK 5081, NDRK 5014, NDRK 5097, NDRK 50030, NDRK 5022, IR 6

Table.5 Most promising cross combinations for different characters along with their per se performance, sca effects and gca effects of parents

Character	Cross Combination	Per se performance	SCA Effect	GCA Effects (L × T)
Days to 50% flowering	NDRK 50032 × PR 124	92.33	-2.00*	Good x Poor
	NDRK 5012 × PR 124	95.00	-1.20**	Good x Good
	NDRK 5014 × PR 124	95.67	-0.97*	Good x Good
	NDRK 5093 × IR 6	96.67	-0.29	Good x Poor
	NDRK 5081 × PR 124	95.00	-0.86*	Good x Good
Days to Maturity	NDRK 50032 × PR 124	116.00	-4.08*	Good x Good
	NDRK 5081 × PR 124	121.33	-3.66**	Good x Good
	NDRK 5093 × PR 124	125.00	1.25	Good x Good
	NDRK 5012 × PR 124	131.00	-1.91*	Good x Good
	Getu × PR 124	127.33	-1.68*	Good x Good
Plant Height (cm)	NDRK 5012 × PR 124	91.43	-3.05**	Good x Good
	NDRK 50030 × PR 124	90.70	-2.50**	Good x Good
	NDRK 50004 × PR 124	86.87	-2.21**	Good x Good
	NDRK 5093 × PR 124	100.47	5.10*	Poor x Good

	NDRK 5022 × IR 6	104.33	8.02*	Poor x Average
Panicle Bearing Tillers	NDRK 5095 × Govind	9.33	0.91**	Good × Poor
	NDRK 50032 × IR 6	9.23	0.59*	Good x Good
	NDRK 5012 × PR 124	8.87	0.27	Good × Poor
	NDRK 50004 × PR 124	8.73	0.31	Good × Poor
	NDRK 5095 × IR 6	8.83	0.39*	Good x Good
Panicle Length (cm)	NDRK 5095 × Govind	19.50	1.67*	Poor x Poor
	NDRK 50032 × IR 6	21.83	1.30*	Good x Good
	PSBRC 90 × IR 6	22.33	0.87	Good x Good
	NDRK 5012 × IR 6	21.67	0.27	Good x Good
	NDRK 50004 × PR 124	20.17	0.16	Good x Average
Spikelets per Panicle	NDRK 50032 × IR 6	189.33	12.31*	Good x Good
	NDRK 5012 × IR 6	181.00	10.11*	Good x Good
	NDRK 5022 × IR 6	144.33	5.33*	Good x Good
	NDRK 5095 × IR 6	168.00	6.17*	Good x Good
	NDRK 5040 × IR 6	148.67	5.62*	Good x Good
Spikelet Fertility (%)	NDRK 5014 × IR 6	84.67	2.41*	Good x Good
	NDRK 5022 × IR 26	84.00	1.47*	Good x Good
	NDRK 5040 × IR 6	84.67	1.44*	Good x Good
	NDRK 50030 × IR 26	83.33	1.29*	Good x Good
	NDRK 5081 × IR 6	83.33	1.37*	Poor x Good
1000-Grain Weight (g)	NDRK 50032 × IR 6	25.28	1.35*	Good x Good
	NDRK 50004 × IR 6	24.69	0.96*	Good x Good
	NDRK 5014 × IR 6	23.91	0.61*	Good x Good
	Getu × IR 26	25.09	0.01	Good x Good
	NDRK 5081 × IR 6	23.35	0.82*	Good x Good
Biological Yield/Plant (g)	NDRK 5022 × Govind	62.33	3.76*	Good x Poor
	NDRK 5081 × IR 6	66.06	5.96*	Good x Good
	NDRK 5095 × PR 124	42.57	3.27*	Good x Poor
	NDRK 50030 × IR 6	63.32	2.84*	Good x Good
	NDRK 5012 × IR 6	61.85	1.87*	Good x Good
Harvest Index (%)	NDRK 5095 × IR 6	44.30	2.18*	Good x Poor
	NDRK 5040 × Govind	47.56	1.42*	Good x Poor
	Getu × PR 124	42.87	1.15*	Good x Good
	NDRK 5097 × Govind	42.09	1.05*	Good x Poor
	NDRK 5093 × PR 124	40.79	-1.45*	Poor × Good
Grain Yield/Plant (g)	NDRK 5014 × IR 6	25.67	1.04	Average x Good
	NDRK 50032 × IR 26	25.08	4.31**	Poor x Average
	NDRK 5022 × IR 6	24.05	0.10	Average x Good
	NDRK 5081 × IR 6	24.96	1.30*	Good x Good
	NDRK 5097 × IR 26	22.84	-0.10	Average × Average

Among the testers, IR 6 was identified as the best general combiner, displaying significantly positive GCA effects for several key traits such as days to 50% flowering, days to maturity, panicle bearing tillers per plant, panicle length, spikelets per panicle, spikelet fertility, 1000-seed weight, biological yield, and grain yield per plant. This suggests that IR 6 contributes favorable alleles that enhance yield potential under sodic conditions. Similarly, IR 26 showed positive effects for most traits and can also be considered a promising parent in breeding programs targeting sodic soils. In contrast, PR 124 and Govind exhibited negative or average GCA effects for most traits, indicating limited utility in hybrid breeding for adverse environments.

Among the lines, NDRK 5081, NDRK 5012, NDRK 5014, NDRK 5097, NDRK 50030, and NDRK 5022 were identified as good general combiners for grain yield and related traits, as indicated in Table 3. For example, NDRK 5081 exhibited significantly positive GCA effects for plant height, biological yield, and grain yield, indicating its potential for yield improvement. NDRK 5012 also showed favorable GCA for panicle number, panicle length, and spikelets per panicle, making it a good candidate for improving panicle architecture. Similarly, NDRK 5014 and NDRK 5097 had positive effects on spikelet fertility and biological yield, while NDRK 50030 and NDRK 5022 were associated with higher grain yield and spikelet fertility. These lines can be effectively utilized in hybridization programs aiming to develop high-yielding rice varieties suitable for sodic environments. Conversely, lines like NDRK 50032 and NDRK 5040 showed poor general combining ability for most traits, including grain yield, suggesting limited value as parents in breeding for sodic tolerance. Some lines, such as PSBRC 90 and NDRK 50004, were average combiners and may still be useful in specific crosses where complementary traits are needed. The results imply that traits such as spikelet fertility, biological yield, and 1000-seed weight, governed predominantly by additive gene action, can be improved through selection-based approaches. These findings align with earlier studies by [Rashid et al., \(2017\)](#), [Choudhary et al., \(2019\)](#), and [Yadav et al., \(2021\)](#), which emphasized the importance of GCA effects in selecting parents for saline and sodic environments.

Table 4 outlines the parents exhibiting significant and desirable general combining ability (GCA) effects for various traits in rice, which are crucial for improving rice varieties under sodic soil conditions. For days to 50%

flowering and days to maturity, the lines NDRK 50032, NDRK 5012, and NDRK 5014 showed desirable GCA effects, making them suitable for breeding early-maturing varieties. These parents could play a significant role in breeding varieties that can adapt to shorter growing seasons, an essential trait for regions with limited water or those affected by drought stress ([Choudhary et al., 2019](#)). For plant height, NDRK 5012, NDRK 50004, and NDRK 50030 were found to have favorable GCA effects. Plant height is a crucial trait for improving mechanized harvesting and plant lodging resistance, both of which are critical for rice cultivation in modern agriculture. Similarly, the trait panicle bearing tillers per plant is another important yield determinant. Parents like NDRK 50032, PSBRC 90, and NDRK 5012, among others, showed desirable GCA for this trait, indicating their potential for enhancing tillering, which directly affects the rice yield per unit area ([Yadav et al., 2021](#)).

In terms of panicle length and spikelets per panicle, NDRK 50032, PSBRC 90, and NDRK 5012 were favorable parents, as these traits are directly related to the grain-bearing capacity of the plant. Panicle length and the number of spikelets per panicle are essential for improving the yield potential of rice, especially under challenging environmental conditions ([Rashid et al., 2017](#)). For spikelet fertility, NDRK 5014, NDRK 5022, and NDRK 5040 exhibited positive GCA effects. Spikelet fertility is a key trait for ensuring high grain set, and its improvement can directly contribute to enhanced rice yield ([Choudhary et al., 2019](#)). As for 1000-grain weight, parents like NDRK 50032, NDRK 50004, and NDRK 5014 exhibited desirable GCA effects, as this trait influences overall yield and grain quality. Larger grain size is often linked with improved grain quality and marketability ([Choudhary et al., 2019](#)).

Regarding biological yield per plant and harvest index, NDRK 5012, NDRK 5014, and NDRK 5097 demonstrated significant positive GCA effects for biological yield, which is indicative of the plant's overall biomass accumulation. The harvest index, which measures the efficiency of biomass conversion into grains, was favorable in NDRK 50032, NDRK 5095, and NDRK 5040. High harvest index is a desirable trait for improving grain yield efficiency, especially in environments with limited resources ([Yadav et al., 2021](#)). Finally, for grain yield per plant, NDRK 5012, NDRK 5081, and NDRK 5097 exhibited significantly favorable GCA effects. Grain yield per plant is the most important

trait in rice breeding programs, and these parents could be instrumental in improving yield potential under challenging soil conditions like sodic soils (Rashid *et al.*, 2017).

The cross NDRK 50032 × PR 124 exhibited the earliest flowering (92.33 days) with significant negative SCA effects (-2.00*), making it a promising combination for early flowering (Table 5). Similarly, NDRK 5012 × PR 124 (95.00 days) showed a negative SCA effect (-1.20**), which also favors early flowering in hybridization programs. NDRK 50032 was found to be a good general combiner for early maturity, as the cross NDRK 50032 × PR 124 matured in 116.00 days. Additionally, NDRK 5081 × PR 124 showed good performance for maturity (121.33 days) and negative SCA effects (-3.66**), indicating it may be a favorable cross for early maturity. For plant height, the crosses NDRK 5012 × PR 124 (91.43 cm) and NDRK 50030 × PR 124 (90.70 cm) demonstrated good performance, while NDRK 5093 × PR 124 (100.47 cm) exhibited a high plant height, which may not be desirable in some breeding programs due to its tall stature. NDRK 5022 × IR 6 (104.33 cm) had a relatively higher height and could be useful for specific breeding needs in certain environmental conditions.

For panicle length, NDRK 50032 × IR 6 (21.83 cm) and PSBRC 90 × IR 6 (22.33 cm) performed well, which is beneficial for improving rice panicle length in breeding programs. Additionally, NDRK 5012 × IR 6 (21.67 cm) also demonstrated significant panicle length. In terms of spikelets per panicle, crosses such as NDRK 50032 × IR 6 (189.33 spikelets) and NDRK 5012 × IR 6 (181.00 spikelets) displayed high potential for increasing panicle productivity. Spikelet fertility, an important determinant of yield, was high in crosses like NDRK 5014 × IR 6 (84.67%) and NDRK 5022 × IR 26 (84.00%).

The combination NDRK 50032 × IR 6 showed good performance for 1000-grain weight (25.28 g) with positive SCA effects (1.35*), while NDRK 50004 × IR 6 (24.69 g) also exhibited favorable grain weight characteristics. The cross NDRK 5081 × IR 6 (23.35 g) showed a moderate weight, but still within a good range for further selection. For biological yield, the cross NDRK 5081 × IR 6 (66.06 g) and NDRK 5022 × Govind (62.33 g) demonstrated high potential for improving rice biomass. The cross NDRK 5095 × IR 6 (44.30%) exhibited high harvest index, indicating a better partitioning of biomass into grains. The cross NDRK

5097 × Govind (42.09%) also had a favorable harvest index. For grain yield, NDRK 50032 × IR 26 (25.08 g) and NDRK 5014 × IR 6 (25.67 g) demonstrated favorable potential for improving yield per plant.

These results indicate that selecting both general and specific combiners for key traits such as flowering time, plant height, panicle productivity, grain weight, and yield can significantly enhance the productivity of rice. Parent lines such as NDRK 50032, NDRK 5012, and NDRK 5093 were identified as good general combiners for early flowering, maturity, and high yield. Specific crosses with high SCA effects, such as NDRK 50032 × PR 124 and NDRK 5012 × PR 124, showed promise for improving multiple agronomic traits simultaneously.

In conclusion, the findings of this study highlight the significant genetic variability and potential for genetic improvement in rice under sodic soil conditions. The analysis of combining ability revealed the importance of both additive and non-additive gene actions in controlling key agronomic traits such as grain yield, spikelet fertility, and panicle length. The identification of superior general combiners like NDRK 50032, NDRK 5012, and IR 6, along with promising specific crosses such as NDRK 50032 × PR 124 and NDRK 5012 × PR 124, underscores the potential for utilizing both hybrid and selection-based breeding strategies to enhance rice productivity. These results provide valuable insights for developing high-yielding, stress-tolerant rice varieties, particularly for challenging sodic soil environments.

Author Contributions

Mohammad Nisar: Conceived the original idea and designed the model the computational framework and wrote the manuscript; Kunvar Gyanendra Kumar: Formal analysis, writing review and editing; Rudra Pratap Singh: Validation, methodology, writing—reviewing

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflict of Interest The authors declare no competing interests.

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