*Original Research Article*

**Gene Action and Combining Ability Studies for** **Grain Yield and its Related Traits in CMS based Rice Hybrids using Line × Tester Analysis**

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ABSTRACT

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| The present study intends to estimate the nature and magnitude of gene action and combining ability for yield and related traits in CMS based rice hybrids developed by crossing three CMS lines with 14 testers in Line × Tester mating design. During *kharif* 2023, 42 F1’s were developed which were evaluated along with their 17 parents in Randomized Block Design (RBD) with three replications during *kharif,* 2024 at the Rice and Wheat Research Centre, Malan, Himachal Pradesh. The observations were recorded for various characters *viz*., days to 50% flowering, days to 75% maturity, plant height at maturity, effective tillers per plant, panicle length, spikelets per panicle, grains per panicle, grain yield per plant, spikelet fertility, 1000-grain weight, grain length, grain breadth and L:B ratio. The analysis of variance for combining ability showed that Lines × Testers had significant differences for all the characters studied which indicated presence of sufficient amount of variation for yield and its component traits. Combining ability analysis revealed that among testers, HPR 2143 and among lines, IR 58025A exhibited desirable general combining ability (GCA) effects for grain yield and majority characters. IR 58025A × HPR 2612 reflected desirable significant specific combining ability (SCA) effects for majority characters studied. Preponderance of non-additive gene action was found in the inheritance of characters which was validated by higher values of SCA variances than their corresponding GCA variances. The study revealed the potential parents and promising cross combination(s) which could be further exploited for heterosis breeding. However, Multi-environment trials will be needed for efficient selection because they help to understand the true genetic potential of genotypes. |

*Keywords: Gene action; CMS; Line x Tester; Randomized Block Design; General Combing Ability; Specific Combining Ability*

1. INTRODUCTION

Rice (*Oryza sativa* L.) is a self-pollinating, short day plant belonging to the family Poaceae. It is a staple food for more than 60% of the world’s population. China and India are the top producers of rice in the world, while Bangladesh and Indonesia are also significant contributors to global rice production. Global area under rice cultivation is 166.09 million hectares with an annual production of 522.08 million tonnes and productivity of 3.14 tonnes per hectare (USDA, 2024). India ranks second with production of 137.83 million tonnes in 47.83 million hectares area and the productivity is 2.88 tonnes per hectare (USDA, 2024).

Cytoplasmic male sterility (CMS) system offers a valuable approach for the commercial exploitation of heterosis (El-Namaky, 2018 and Liao et al. 2021). Knowledge of gene action helps in the selection of parents for use in hybridization programmes and also in the choice of appropriate breeding procedures for the genetic improvement of various characters. Combining ability studies helps in selecting the best parental lines for hybridization and identifying the promising cross combinations (Kempthorne, 1957). GCA signifies additive gene effects contributed by a parent, indicating its overall breeding value, whereas SCA is related to non-additive gene effects and indicates the deviation of hybrid performance from the parents used, offering insights into the unique combination of traits exhibited in hybrids (Bradshaw, 2017; Parimala et al. 2018; Salem et al. 2020). Altogether, a thorough understanding of GCA and SCA enables breeders to make informed decisions for hybridization programmes, ultimately leading to the development of rice varieties that exhibit improved yield, quality, disease resistance and other agronomically important traits.

Line × Tester analysis is one of the powerful and widely used biometrical mating design which help breeders to evaluate the genetic potential of different genotypes, identify superior parents and understand the gene action involved in the inheritance of different traits. Therefore, Line × Tester analysis is crucial in rice breeding as it provides deep insights into the genetic control of traits and help in development of hybrid rice with enhanced yield and biotic/abiotic stress tolerance.

Therefore, present investigation was done for a range of agro-morphological characters to estimate the nature and magnitude of gene action and combining ability in order to identify potential parents and promising cross combinations in rice using Line × Tester analysis.

**2.** **EXPERIMENTAL LOCATION/ MATERIALS AND METHODS**

**2.1 Experimental location:** The present study was conducted at the Rice and Wheat Research Centre, Malan, H.P., India during *kharif*, 2023 and *kharif*, 2024 to estimate the nature and magnitude of gene action and combining ability for yield and related traits in CMS based rice hybrids.

The Research Centre lies at a latitude of 32°12' N and longitude of 76°20' E in the lap of majestic Dhauladhar range of North Western Himalayas. The elevation above mean sea level is 950 m with temperature ranging from 15.6 ºC to 28.6 ºC, observing sub-humid mid-hill conditions. The soil type is silty clay loam with pH ranging from 5.8 to 6.0.

**2.2 Experimental materials:** The experimental materials (Table 1) consisted of three CMS lines *viz*., IR 58025A, IR 79156A and IR 68897A and 14 testers *viz*., HPR 1068, HPR 1156, HPR 2143, HPR 2612, HPR 2656, HPR 2720, HPR 2795, HPR 2880, HPU 2216, RP 2421, Kasturi, Koshikari, Naggar Dhan and Varun Dhan.

**2.3 Development of F1 hybrids:** The crossing was done in *kharif,* 2023 in Line × Tester mating design (Kempthorne, 1957) and 42 F1 hybrids were developed. The emasculation of the female parents was done using hand emasculation method (only clipping of panicles by scissors). The panicles of the males were cut using scissors before anther dehiscence and taken to the location of the female parent for pollination. After the pollination was done, the butter paper bag was again replaced over the female parent and the details of the male and female parents along with the date of emasculation and pollination were recorded on the tag and attached to the female panicle (Coffman and Herrera, 1980). After maturity, the bagged panicles were harvested and from each cross, the hybrid seeds were separately collected, sun dried and properly stored.

**2.4 Evaluation of F1 hybrids along with their parents:** The F1 hybrids along with their parents were evaluatedin a Randomized Block Design (RBD) with three replications at Rice and Wheat Research Centre, Malan, H.P. during *kharif*, 2024.

The seeds were sown initially in nursery, later transplantedto the main field after 25 days with an inter-row spacing of 20cm and plant-to-plant spacing of 15cm. Standard agronomic package of practices were followed and observations were recorded for various characters *viz*., days to 50% flowering, days to 75% maturity, plant height at maturity, effective tillers per plant, panicle length, spikelets per panicle, grains per panicle, grain yield per plant, spikelet fertility, 1000-grain weight, grain length, grain breadth and L:B ratio.

**Table 1: List of rice genotypes and their parentage/source used in the study**

|  |  |
| --- | --- |
| **Genotypes** | **Parentage/Source** |
| **Lines** |  |
| 1. IR 58025A | Wild Abortive (WA) – IRRI Philippines / IIRR, Hyderabad |
| 2. IR 79156A | Wild Abortive (WA) – IRRI Philippines / IIRR, Hyderabad |
| 3. IR 68897A | Wild Abortive (WA) – IRRI Philippines / IIRR, Hyderabad |
| **Testers** |  |
| 1. HPR 1068 | IR 42015-83-3-22/IR 9758-K2 |
| 2. HPR 1156 | IR 32429-122-3-1-2/IR 31868-64-2-3-3-3 |
| 3. HPR 2143 | Phul Patas/HUP 741 |
| 4. HPR 2612 | Hassan Serai/T23//IR 66295-36-2 |
| 5. HPR 2656 | RP2421/VL Dhan 221 |
| 6. HPR 2720 | Pure line selection from Begmi (IC455333) |
| 7. HPR 2795 | Selection from IC 3131180 germplasm |
| 8. HPR 2880 | HPU2216/Tetep |
| 9. HPU 2216 | IR8/IR2053-521-1-1//IR36 |
| 10. RP 2421 | IR36/Kathwar |
| 11. Kasturi | Basmati 370/CR 88-17-1-5 |
| 12. Koshikari | *Japonica* rice germplasm |
| 13.Naggar Dhan | Ching Shi-15 (Acc.36852) |
| 14. Varun Dhan | Kunjen 4 (HPR K 2001) |

3. results and discussionS

**3.1** **Analysis of variance for combining ability:** The analysis of variance for combining ability revealed significant differences among lines for characters *viz*., plant height at maturity, grain length and L:B ratio whereas testers showed significant differences for characters *viz*., days to 50% flowering, days to 75% maturity, plant height at maturity, effective tillers per plant, panicle length, spikelets per panicle, grains per panicle, grain yield per plant and spikelet fertility (Table 2). Lines × Testers revealed significant differences for all the characters studied which indicated the presence of sufficient amount of variability. Similar results had been reported earlier by Saleem et al. (2010), Ramesh et al. (2018), Saikiran et al. (2018), El-Shamey et al. (2022) and Nagamani et al. (2022) wherein significant differences in Lines × Testers were found for most of the traits.

Krishna et al. (2024) observed significant variances in Lines × Testers for most of the traits except days to 50% flowering, ear bearing tillers, panicle length, filled grains, kernel length, kernel breadth and grain yield.

**3.2** **Contribution of Lines, Testers and Line × Tester:** The proportional contribution of lines (0.03% - 15.40%) was found to be lower than the testers (37.01% - 77.16%). Contribution of Line × Tester ranged between (21.68% - 50.41%) (Table 3). Significant contribution of testers as compared to the lines has been reported earlier by Hasan et al. (2015) for characters *viz*., panicle length (38.01%), number of spikelets per panicle (46.92%) and 1000-grain weight (62.92%).

**3.3 Estimates of combining ability variances and gene action:** To deal with the genetic heterogeneity resulting from hybridization, suitable breeding strategies are necessary which depend extensively upon the type of gene action involved. The mating design line × tester technique is valuable in understanding gene action, as it provides estimates for both general combining ability variances (σ2GCA) and specific combining ability variances (σ2SCA). The estimates of genetic components of variance (Table 4) revealed higher levels of σ2SCA than σ2GCA for all characters, indicating important role of non-additive gene action in all the characters which was further assisted by the results obtained from the average degree of dominance, which highlighted the existence of over-dominance (>1) for the inheritance of all traits under study except grain length, grain breadth and L:B ratio. It suggests that heterosis breeding will be rewarding.

Similar studies were conducted by Sala et al. (2016), Ramesh et al. (2018), Anis et al. (2019), Singh et al. (2019), Anandlekshmi et al. (2020), Yousef et al. (2020), Hussein et al. (2021), Ray et al. (2021), Kumar and Pandey (2023), Tiwari et al. (2024) and Nivedha et al. (2024) wherein they reported the predominance of non-additive gene action and GCA/SCA ratio < 1 in their findings. In earlier studies, Shrivastav et al. (2024) reported the presence of non-additive gene action in the inheritance of grain yield per plant and other yield contributing traits.

**Table 2: Analysis of variance for combining ability analysis in Line × Tester design for grain yield and its related traits in rice**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Mean Sum of Squares** | | | | | |
| **Sources** | **Replications** | **Lines** | **Testers** | **Lines × Testers** | **Error** |
| **Traits df** | **2** | **2** | **13** | **26** | **82** |
| Days to 50% flowering | 4.15 | 0.22 | 82.25\* | 13.84\* | 1.18 |
| Days to 75% maturity | 1.34 | 11.65 | 119.06\* | 16.73\* | 1.30 |
| Plant height at maturity | 40.68 | 1505.01\* | 837.84\* | 217.13\* | 10.97 |
| Effective tillers per plant | 0.91 | 5.30 | 12.75\* | 5.58\* | 0.51 |
| Panicle length | 2.17 | 15.56 | 36.50\* | 6.06\* | 1.01 |
| Spikelets per panicle | 1681.05 | 1309.66 | 7717.35\* | 3108.44\* | 152.58 |
| Grains per panicle | 1197.39 | 1313.23 | 9531.61\* | 3484.52\* | 162.65 |
| Grain yield per plant | 0.02 | 24.55 | 244.12\* | 114.02\* | 2.37 |
| Spikelet fertility | 1.83 | 422.04 | 554.81\* | 237.45\* | 13.95 |
| 1000-grain weight | 3.73 | 20.22 | 15.49 | 9.46\* | 0.90 |
| Grain length | 0.05 | 2.18\* | 0.94 | 0.63\* | 0.03 |
| Grain breadth | 0.02 | 0.21 | 0.17 | 0.08\* | 0.01 |
| L:B ratio | 0.02 | 1.47\* | 0.66 | 0.43\* | 0.01 |

\* *Significant at P ≤ 0.05*

**Table 3: Proportional contribution of lines, testers and Line × Tester for grain yield and its related traits in rice**

|  |  |  |  |
| --- | --- | --- | --- |
| **Traits** | **Contribution (%)** | | |
| **Lines** | **Testers** | **Line × Tester** |
| Days to 50% flowering | 0.03 | 74.80 | 25.17 |
| Days to 75% maturity | 1.16 | 77.16 | 21.68 |
| Plant height at maturity | 15.40 | 55.72 | 28.88 |
| Effective tillers per plant | 3.30 | 51.57 | 45.14 |
| Panicle length (cm) | 4.69 | 71.55 | 23.76 |
| Spikelets per panicle | 1.43 | 54.59 | 43.98 |
| Grains per panicle | 1.21 | 57.07 | 41.72 |
| Grain yield per plant (g) | 0.79 | 51.29 | 47.91 |
| Spikelet fertility (%) | 5.93 | 50.68 | 43.38 |
| 1000-grain weight (g) | 8.29 | 41.30 | 50.41 |
| Grain length (mm) | 13.16 | 37.01 | 49.83 |
| Grain breadth (mm) | 8.88 | 46.60 | 44.52 |
| L:B ratio | 12.97 | 38.01 | 49.02 |

**Table 4: Estimates of combining ability variances and gene action for grain yield and its related traits in rice**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Traits** | **σ2GCA** | **σ2SCA** | **GCA/SCA** | **σ2A**  **(F=1)** | **σ2D**  **(F=1)** | **Average degree of dominance** |
|
| Days to 50% flowering | 0.245 | 4.221 | 0.058 | 0.489 | 4.221 | 2.054 |
| Days to 75% maturity | 0.375 | 5.142 | 0.073 | 0.749 | 5.142 | 2.268 |
| Plant height at maturity | 3.020 | 68.720 | 0.044 | 6.040 | 68.720 | 8.290 |
| Effective tillers per plant | 0.026 | 1.690 | 0.015 | 0.053 | 1.690 | 1.300 |
| Panicle length | 0.118 | 1.685 | 0.070 | 0.235 | 1.685 | 1.298 |
| Spikelets per panicle | 15.977 | 985.285 | 0.016 | 31.954 | 985.285 | 31.389 |
| Grains per panicle | 21.069 | 1107.289 | 0.019 | 42.139 | 1107.289 | 33.276 |
| Grain yield per plant | 0.429 | 37.215 | 0.012 | 0.858 | 37.215 | 6.100 |
| Spikelet fertility | 1.275 | 74.502 | 0.017 | 2.550 | 74.502 | 8.631 |
| 1000-grain weight | 0.028 | 2.852 | 0.010 | 0.057 | 11.409 | 3.378 |
| Grain length | 0.002 | 0.203 | 0.010 | 0.004 | 0.203 | 0.450 |
| Grain breadth | 0.004 | 0.025 | 0.161 | 0.001 | 0.025 | 0.158 |
| L:B ratio | 0.002 | 0.137 | 0.014 | 0.003 | 0.137 | 0.371 |

**3.4: Estimates of general combining ability (GCA) effects:** Estimates of GCA effects help in selection of parents for utilization in hybridization programs that aim to develop high-yielding varieties. GCA effect is linked to the fixable additive component of variance.The GCA effects of 17 parents *i.e.,* three CMS lines and 14 testers for various traits were calculated and are presented in Table 5. The list of promising parents with highest desirable GCA effects for all the traits is shown in Table 6. This information is essential for breeders who seek to create superior plant varieties with desirable characteristics. Thus, by understanding the GCA effects of different parents, breeders can make informed decisions and develop effective hybridization strategies which helps in development of superior hybrids.

The estimates of GCA effects revealed that out of lines, IR 58025A was found to be a good general combiner for grain yield per plant along with four other characters *viz*., days to 75% maturity, grains per panicle, spikelet fertility and 1000-grain weight. The results were similar to the findings of Lakra (2020), Yousef et al. (2020) and Azad et al. (2022) wherein IR 58025A was reported as good general combiner for yield and related traits. El-Shamey et al. (2022) reported IR 58025A as a good general combiner for traits *viz*., panicle length and grain yield per plant.

However, among the 14 testers, HPR 2143 stood out as a potential parent for breeding due to its possession of desirable GCA effects for 11 traits *viz*., days to 50% flowering, days to 75% maturity, panicle length, spikelets per panicle, grains per panicle, grain yield per plant, spikelet fertility, 1000-grain weight, grain length, grain breadth and L:B ratio. Similarly, Kasturi was also found to be good general combiner as it had desirable GCA effects for seven characters under study *viz*., panicle length, spikelets per panicle, grains per panicle, grain yield per plant, spikelet fertility, grain breadth and L:B ratio, making it suitable for future breeding programmes of rice. Hasan et al. (2017) also reported significant and desirable GCA effects for most of the yield and related traits in rice. Parents, *viz.,* HPR 1156, HPR 2795 and HPR 2720 were identified as good general combiners for grain yield (Table 6).

**Table 5: Estimates of GCA effects of lines and testers for grain yield and its related traits in rice**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Parents** | **DTF** | **DTM** | **PH** | **ETPP** | **PL** | **SPP** | **GPP** | **GYPP** | **SF** | **TGW** | **GL** | **GB** | **L:B** | |
| **Lines** | | | | | | | | | | | | | |
| IR 58025A | 0.02 | -0.49\* | 2.41\* | -0.41\* | -0.51\* | -2.72 | 4.29\* | 0.82\* | 3.50\* | 0.56\* | -0.05 | 0.06\* | -0.09\* | |
| IR 79156A | -0.08 | -0.06 | 4.41\* | 0.24\* | 0.67\* | -3.70 | -6.33\* | -0.14 | -2.67\* | -0.78\* | -0.20\* | 0.02 | -0.13\* | |
| IR 68897A | 0.06 | 0.56\* | -6.82\* | 0.16 | -0.17 | 6.42\* | 2.04 | -0.68\* | -0.84 | 0.21 | 0.25\* | -0.08\* | 0.21\* | |
| **SE (gi) ±** | 0.17 | 0.18 | 0.51 | 0.11 | 0.15 | 1.91 | 1.97 | 0.24 | 0.58 | 0.15 | 0.24 | 0.01 | 0.02 | |
| **SE (gi-gj) ±** | 0.24 | 0.25 | 0.72 | 0.16 | 0.22 | 2.70 | 2.78 | 0.34 | 0.82 | 0.21 | 0.03 | 0.01 | 0.03 | |
| **Testers** | | | | | | | | | | | | | |
| HPR 1068 | -0.83\* | -0.32 | -2.77\* | 0.06 | -1.11\* | -20.29\* | -12.73\* | -0.39 | 3.88\* | 0.71\* | 0.22\* | 0.18\* | -0.15\* | |
| HPR 1156 | -0.38 | 4.35\* | 7.12\* | -0.27 | 0.22 | 6.05 | 12.57\* | 6.28\* | 4.41\* | 0.00 | 0.02 | -0.21\* | 0.32\* | |
| HPR 2143 | -2.94\* | -2.65\* | 6.01\* | -0.05 | 1.96\* | 16.38\* | 19.53\* | 2.45\* | 4.88\* | 0.74\* | 0.26\* | -0.09\* | 0.23\* | |
| HPR 2612 | -0.71 | -1.21\* | -15.77\* | 0.14 | -0.48 | -21.33\* | -26.98\* | -5.75\* | -6.17\* | -1.99\* | 0.80\* | -0.07\* | 0.52\* | |
| HPR 2656 | -2.71\* | -2.98\* | -4.74\* | 2.36\* | -2.22\* | -9.81\* | -4.95 | 4.69\* | 1.84 | -0.86\* | -0.17\* | -0.04 | -0.03 | |
| HPR 2720 | 5.17\* | 7.02\* | 12.12\* | -0.49\* | 2.30\* | 74.05\* | 61.28\* | 5.25\* | 1.13 | -1.01\* | -0.11\* | 0.06\* | -0.15\* | |
| HPR 2795 | 4.73\* | 4.35\* | 19.75\* | -0.60\* | 3.52\* | 44.49\* | 55.05\* | 5.96\* | 8.42\* | 0.69\* | -0.07 | 0.15\* | -0.23\* | |
| HPU 2216 | 2.95\* | 2.35\* | -6.07\* | -0.34 | -0.78\* | -11.92\* | -6.95 | 2.57\* | 2.82\* | 1.33\* | -0.11\* | -0.13\* | 0.12\* | |
| RP 2421 | -0.16 | -0.54 | -2.85\* | -1.53\* | -1.04\* | -122.77\* | -7.17 | -3.56\* | 3.55\* | -1.08\* | 0.17\* | 0.09\* | -0.07 | |
| Kasturi | 4.29\* | 6.68\* | 8.82\* | -1.86\* | 3.56\* | 14.71\* | 32.72\* | 3.01\* | 11.24\* | 0.29 | 0.02 | -0.21\* | 0.31\* | |
| Koshikari | -3.16\* | -3.65\* | -5.88\* | -0.49\* | -1.04\* | -14.18\* | -26.76\* | -7.17\* | 9.15\* | 2.58\* | 0.01 | 0.09\* | 0.09\* | |
| Naggar Dhan | -3.27\* | -3.32\* | -9.92\* | 1.69\* | -0.67\* | -8.66\* | -23.10\* | -6.92\* | -10.22\* | -1.81\* | -0.07 | 0.09\* | -0.16\* | |
| Varun Dhan | -1.71\* | -1.65\* | 1.30 | -0.34 | -2.04\* | -30.77\* | -51.73\* | -7.71\* | -17.15\* | 1.23\* | -0.66\* | 0.17\* | -0.53\* | |
| HPR 2880 (C) | -1.27\* | -1.54\* | -7.11\* | 1.73\* | -2.18\* | -25.96\* | -20.80\* | 1.31\* | 0.53 | -0.82\* | -0.29\* | -0.06\* | -0.07 | |
| **SE (gi) ±** | 0.36 | 0.38 | 1.10 | 0.24 | 0.33 | 4.12 | 4.25 | 0.51 | 1.24 | 0.32 | 0.05 | 0.02 | 0.04 | |
| **SE (gi-gj) ±** | 0.51 | 0.54 | 1.56 | 0.34 | 0.47 | 5.82 | 6.01 | 0.73 | 1.76 | 0.45 | 0.07 | 0.03 | 0.06 | |
| *\* Significant at P ≤ 0.05*  *DTF- Days to 50% flowering, DTM- Days to 75% maturity, PH- Plant height (cm), ETPP- Effective tillers per plant, PL- Panicle length (cm), SPP- Spikelets per panicle, GPP- Grains per panicle, GYPP- Grain yield per plant (g), SF- Spikelet fertility (%), TGW- 1000-grain weight (g), GL- Grain length (mm), GB- Grain breadth (mm) and L:B- L:B ratio* | | | | | | | | | | | | | |

|  |  |
| --- | --- |
| **Table 6: Promising parents based on highly significant GCA effects for grain yield and its related traits in rice** | |
| **Traits** | **Genotypes** |
| Days to 50% flowering | Naggar Dhan, Koshikari and HPR 2143 |
| Days to 75% maturity | Naggar Dhan, Koshikari and HPR 2656 |
| Plant height at maturity | HPR 2612, Naggar Dhan and IR 68897A |
| Effective tillers per plant | HPR 2656, Naggar Dhan and IR 79156A |
| Panicle length | Kasturi, HPR 2795 and HPR 2720 |
| Spikelets per panicle | HPR 2720, HPR 2795 and HPR 2143 |
| Grains per panicle | HPR 2720, HPR 2795 and Kasturi |
| Grain yield per plant | HPR 1156, HPR 2795 and HPR 2720 |
| Spikelet fertility | Kasturi, Koshikari and HPR 2795 |
| 1000-grain weight | Koshikari, HPU 2216 and Varun Dhan |
| Grain length | HPR 2612, HPR 2143 and IR 68897A |
| Grain breadth | HPR 1156, Kasturi and HPU 2216 |
| L:B ratio | HPR 2612, HPR 1156 and Kasturi |

**3.5: Estimates of specific combining ability (SCA) effects:** The specific combining ability (SCA) effects are closely linked to hybrid vigour, which can be utilized to produce high-yielding varieties of rice. None of the cross combination(s) exhibited desirable and significant SCA effects for all the studied characters simultaneously, consistent with the findings of Kumari et al. (2014), Devi et al. (2017), Yuga et al. (2018), Gramaje et al. (2020) and Latha et al. (2020). However, cross combination *viz*., IR 58025A × HPR 2612, exhibited notable performance by manifesting desirable and significant SCA effects across nine characters *viz*., panicle length, spikelets per panicle, grains per panicle, grain yield per plant, spikelet fertility, 1000-grain weight, grain length, grain breadth and L:B ratio (Table 7). In a similar study, Kirubha et al. (2019) reported significant SCA effects in hybrids for majority characters studied. Hybrids with significant negative SCA effects for days to 50% flowering and plant height coupled with positive SCA effect for other traits had been reported earlier by Deepika et al. (2023).

The hybrids displaying the highest SCA effects involved all possible combinations between parents of good, low and average combining ability (Table 8). Thus, there was inconsistent relationship between GCA and SCA which revealed that GCA effects of parents were poor predictors of SCA effects. IR 68897A × Koshikari had highly significant SCA for grain yield per plant, despite both its parents having poor GCA for the trait. Similar scenarios were also reported earlier by Latha et al. ([2013](https://link.springer.com/article/10.1007/s10681-019-2542-y#ref-CR19)), Huang et al. ([2015](https://link.springer.com/article/10.1007/s10681-019-2542-y#ref-CR60)) and Yuga et al. ([2018](https://link.springer.com/article/10.1007/s10681-019-2542-y#ref-CR57)). The hybrids displaying the highest SCA effects with high × high combiners is attributed to the interaction between positive alleles of both parents, while that from low × low combiners is due to overdominance/epistasis. Similar findings for low × high and low × low were reported by Rahimi et al. (2010) and Reddy et al. (2024).

**Table 7: Estimates of SCA effects of crosses for grain yield and its related traits in rice**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Crosses** | **DTF** | **DTM** | **PH** | **ETPP** | **PL** | **SPP** | **GPP** | **GYPP** | **SF** | **TGW** | **GL** | **GB** | **L:B** |
| IR 58025A × HPR 1068 | 0.87 | 1.94\* | -6.26\* | 1.00\* | -0.27 | 3.31 | 2.12 | 3.35\* | 0.59 | -0.43 | -0.36\* | -0.01 | -0.16\* |
| IR 79156A × HPR 1068 | 0.30 | 0.17 | -1.15 | -1.32\* | 1.77\* | 10.63 | -2.16 | -6.68\* | -7.07\* | 1.28\* | 0.14 | 0.16\* | -0.12 |
| IR 68897A × HPR 1068 | -1.17 | -2.11\* | 7.41\* | 0.32 | -1.50\* | -13.94 | 0.04 | 3.33\* | 6.48\* | -0.85 | 0.22\* | -0.15\* | 0.28\* |
| IR 58025A × HPR 1156 | 1.10 | 0.83 | 12.30\* | 1.45\* | 1.62\* | 21.09\* | 19.38\* | -2.88\* | 1.11 | -1.38\* | -0.42\* | 0.03 | -0.30\* |
| IR 79156A × HPR 1156 | 0.19 | -0.60 | -0.70 | -1.32\* | 0.44 | -2.15 | -6.79 | 4.28\* | -2.98 | -0.68 | 0.70\* | -0.12\* | 0.56\* |
| IR 68897A × HPR 1156 | -1.29\* | -0.22 | -11.59\* | -0.13 | -2.05\* | -18.94\* | -12.59 | -1.40 | 1.87 | 2.06\* | -0.27\* | 0.09\* | -0.27\* |
| IR 58025A × HPR 2143 | -1.02 | -0.06 | 0.19 | 0.11 | -1.79\* | -26.24\* | -20.69\* | -1.73 | 0.97 | -1.12\* | -0.22\* | -0.09\* | 0.01 |
| IR 79156A × HPR 2143 | 2.41\* | 2.17\* | 10.85\* | 0.35 | 0.92 | -10.48 | 2.47 | 5.04\* | 6.26\* | 0.58 | -0.34\* | 0.05 | -0.25\* |
| IR 68897A × HPR 2143 | -1.40\* | -2.11\* | -11.04\* | -0.46 | 0.87 | 36.73\* | 18.22\* | -3.31\* | -7.23\* | 0.54 | 0.56\* | 0.04 | 0.24\* |
| IR 58025A × HPR 2612 | 0.10 | -0.17 | 6.07\* | -1.18\* | 1.99\* | 21.02\* | 38.27\* | 10.12\* | 14.04\* | 2.62\* | 0.75\* | -0.30\* | 0.85\* |
| IR 79156A × HPR 2612 | -2.48\* | -2.94\* | -0.15 | 2.05\* | -1.19\* | -14.11 | -27.01\* | -5.68\* | -11.23\* | -2.77\* | -0.63\* | 0.26\* | -0.70\* |
| IR 68897A × HPR 2612 | 2.38\* | 3.11\* | -5.93\* | 0.87\* | -0.80 | -6.90 | -11.26 | -4.44\* | -2.81 | 0.14 | -0.12 | 0.04 | -0.14\* |
| IR 58025A × HPR 2656 | 1.43\* | 0.94 | -3.63 | -0.52 | 0.40 | 36.50\* | 33.34\* | -0.68 | 2.26 | -1.78\* | 0.02 | -0.08\* | 0.09 |
| IR 79156A × HPR 2656 | 0.19 | 0.84 | -2.63 | 0.50 | -0.68 | -29.63\* | -34.60\* | 2.13\* | -6.34\* | 1.40\* | 0.19\* | 0.16\* | -0.13 |
| IR 68897A × HPR 2656 | -1.62\* | -1.78\* | 6.26\* | 0.02 | 0.28 | -6.87 | 1.26 | -1.45 | 4.08 | 0.38 | -0.20\* | -0.08 | 0.04 |
| IR 58025A × HPR 2720 | -0.46 | 0.27 | -5.93\* | -0.78 | -2.34\* | -76.80\* | -63.55\* | -9.93\* | 0.17 | 0.26 | 0.16 | 0.09\* | -0.02 |
| IR 79156A × HPR 2720 | -1.03 | -0.49 | -0.70 | 1.24\* | 1.36\* | 58.96\* | 58.51\* | 13.32\* | 4.25 | 0.52 | 0.48\* | -0.05 | 0.27\* |
| IR 68897A × HPR 2720 | 1.49\* | 0.22 | 6.63\* | -0.46 | 0.98 | 17.84\* | 5.03 | -3.39\* | -4.43\* | -0.79 | -0.64\* | -0.04 | -0.25\* |
| IR 58025A × HPR 2795 | 0.32 | -0.73 | -2.67 | 0.00 | -0.68 | 31.53\* | 31.12\* | 3.90\* | 0.31 | -1.08 | -0.11 | 0.17\* | -0.24\* |
| IR 79156A × HPR 2795 | 0.08 | -0.16 | -6.33\* | -2.65\* | -1.42\* | -45.04\* | -40.60\* | -8.73\* | 1.41 | 0.97 | 0.51\* | -0.17\* | 0.44\* |
| IR 68897A × HPR 2795 | -0.40 | 0.89 | 9.00\* | 2.65\* | 2.09\* | 13.50 | 9.48 | 4.83\* | -1.72 | 0.11 | -0.40\* | -0.01 | -0.20\* |
| IR 58025A × HPU 2216 | -3.24\* | -6.06\* | 1.48 | 1.18\* | -0.60 | 0.39 | -0.43 | 2.81\* | -0.10 | -1.40\* | 0.05 | 0.06 | -0.08 |
| IR 79156A × HPU 2216 | 3.52\* | 3.51\* | 12.70\* | -0.47 | 0.88 | 4.93 | 13.07 | 1.71 | 6.25\* | -0.44 | -0.36\* | -0.11\* | -0.02 |
| IR 68897A × HPU 2216 | -0.29 | 2.56\* | -14.19\* | -0.72 | -0.28 | -5.31 | -12.63 | -4.53\* | -6.15\* | 1.83\* | 0.31\* | 0.05 | 0.10 |
| IR 58025A × RP 2421 | 0.87 | 0.83 | -3.52 | 0.37 | 0.88 | 12.02 | 1.90 | 1.31 | -4.70\* | -0.13 | 0.65\* | -0.16\* | 0.48\* |
| IR 79156A × RP 2421 | 1.30\* | 1.73\* | -2.30 | -1.17\* | -0.53 | -25.56\* | -17.93\* | -2.03\* | 3.63 | 1.23\* | -0.32\* | 0.13\* | -0.29\* |
| IR 68897A × RP 2421 | -2.17\* | -2.56\* | 5.82\* | 0.80 | -0.35 | 13.54 | 16.04\* | 0.71 | 1.07 | -1.09\* | -0.33\* | 0.02 | -0.19\* |
| *\* Significant at P ≤ 0.05* |  |  |  |  |  |  |  |  |  |  |  |  | *continued..* |

**Table 7: Estimates of SCA effects of crosses for** **grain yield and its related traits in rice (continue)**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Crosses** | **DTF** | **DTM** | **PH** | **ETPP** | **PL** | **SPP** | **GPP** | **GYPP** | **SF** | **TGW** | **GL** | **GB** | **L:B** |
| IR 58025A × Kasturi | 2.76\* | 2.60\* | -4.74\* | 0.15 | 0.29 | 15.65\* | 13.34 | 0.74 | -0.69 | -1.64\* | -0.13 | -0.03 | -0.05 |
| IR 79156A × Kasturi | -1.14 | -1.49\* | 5.04\* | 0.28 | 0.33 | 0.74 | -0.49 | -2.70\* | 0.47 | -0.57 | -0.17 | -0.12\* | 0.11 |
| IR 68897A × Kasturi | -1.62\* | -1.11 | -0.30 | -0.42 | -0.61 | -16.39\* | -12.86 | 1.96\* | 0.22 | 2.21\* | 0.30\* | 0.15\* | -0.06 |
| IR 58025A × Koshikari | 1.21 | 1.60\* | 4.41\* | -2.11\* | 0.21 | -32.80\* | -35.28\* | -10.07\* | -5.51\* | 1.61\* | -0.47\* | 0.24\* | -0.51\* |
| IR 79156A × Koshikari | -0.03 | 0.17 | 3.18 | 1.13\* | 0.14 | 30.30\* | 42.77\* | 2.48\* | 11.03\* | 1.74\* | 0.21\* | 0.03 | 0.00 |
| IR 68897A × Koshikari | -1.17 | -1.78\* | -7.59\* | 0.98\* | -0.35 | 2.50 | -7.48 | 7.59\* | -5.52\* | -3.35\* | 0.26\* | -0.27\* | 0.51\* |
| IR 58025A × Naggar Dhan | -2.02\* | -0.73 | -5.00\* | -0.19 | -1.05 | -37.65\* | -49.06\* | -3.65\* | -12.66\* | 2.61\* | -0.01 | 0.20\* | -0.25\* |
| IR 79156A × Naggar Dhan | -0.92 | -0.83 | 2.67 | 0.50 | 1.10 | 42.78\* | 64.88\* | 2.51\* | 18.44\* | -2.15\* | -0.46\* | -0.07 | -0.13 |
| IR 68897A × Naggar Dhan | 2.94\* | 1.56\* | 2.34 | -0.31 | -0.06 | -5.13 | -15.82\* | 1.15 | -5.78\* | -0.45 | 0.47\* | -0.12\* | 0.38\* |
| IR 58025A × Varun Dhan | -2.90\* | -1.73\* | 5.22\* | -0.70 | 0.43 | 11.79 | 5.01 | 2.26\* | -1.91 | 1.41\* | 0.03 | -0.04 | 0.06 |
| IR 79156A × Varun Dhan | 0.52 | 0.51 | -11.67\* | 0.20 | -1.75\* | -2.45 | -10.82 | -3.98\* | -6.63\* | -0.96 | 0.23\* | -0.09\* | 0.21\* |
| IR 68897A × Varun Dhan | 2.38\* | 1.22 | 6.45\* | 0.50 | 1.31\* | -9.35 | 5.81 | 1.72 | 8.54\* | -0.45 | -0.26\* | 0.12\* | -0.27\* |
| IR 58025A × HPR 2880 | 0.98 | 0.49 | 2.07 | 1.22\* | 0.92 | 20.20\* | 24.53\* | 4.45\* | 6.10\* | 0.45 | 0.10 | -0.07 | 0.12 |
| IR 79156A × HPR 2880 | -2.92\* | -2.60\* | -8.82\* | 0.68 | -1.38\* | -18.93\* | -41.30\* | -1.67 | -17.48\* | -0.15 | -0.19\* | -0.08 | 0.04 |
| IR 68897A × HPR 2880 | 1.94\* | 2.11\* | 6.74\* | -1.91\* | 0.46 | -1.28 | 16.78\* | -2.78\* | 11.38\* | -0.30 | 0.09 | 0.15\* | -0.17\* |
| **SE (sij) ±** | 0.63 | 0.66 | 1.91 | 0.41 | 0.58 | 7.13 | 7.36 | 0.89 | 2.16 | 0.55 | 0.09 | 0.04 | 0.07 |
| **SE (sij-skl) ±** | 0.89 | 0.93 | 2.70 | 0.58 | 0.82 | 10.09 | 10.41 | 1.26 | 3.05 | 0.77 | 0.13 | 0.06 | 0.10 |
| *\* Significant at P ≤ 0.05* |  |  |  |  |  |  |  |  |  |  |  |  |  |
| *DTF- Days to 50% flowering, DTM- Days to 75% maturity, PH- Plant height (cm), ETPP- Effective tillers per plant, PL- Panicle length (cm), SPP- Spikelets per panicle, GPP- Grains per panicle, GYPP- Grain yield per plant (g), SF- Spikelet fertility (%), TGW- 1000-grain weight (g), GL- Grain length (mm), GB- Grain breadth (mm) and L:B- L:B ratio* | | | | | | | | | | | | | |

Table 8: Promising parents based on GCA effects for grain yield and its related traits in rice

|  |  |  |
| --- | --- | --- |
| **Traits** | **Crosses** | **GCA effects of parents** |
| Days to 50% flowering | IR 58025A × HPU 2216  IR 79156A × HPR 2880  IR 58025A × Varun Dhan | Average × Poor  Average × Good  Average × Good |
| Days to 75% maturity | IR 58025A × HPU 2216  IR 79156A × HPR 2612  IR 79156A × HPR 2880 | Good × Poor  Average × Good  Average × Good |
| Plant height at maturity | IR 68897A × HPU 2216  IR 79156A × Varun Dhan  IR 68897A × HPR 1156 | Good × Good  Poor × Average  Good × Poor |
| Effective tillers per plant | IR 68897A × HPR 2795  IR 79156A × HPR 2612  IR 58025A × HPR 1156 | Average × Poor  Good × Average  Poor × Average |
| Panicle length | IR 68897A × HPR 2795  IR 58025A × HPR 2612  IR 79156A × HPR 1068 | Average × Good  Poor × Average  Average × Poor |
| Spikelets per panicle | IR 79156A × HPR 2720  IR 79156A × Naggar Dhan  IR 68897A × HPR 2143 | Average × Good  Average × Poor  Good × Good |
| Grains per panicle | IR 79156A × Naggar Dhan  IR 79156A × HPR 2720  IR 79156A × Koshikari | Poor × Poor  Poor × Good  Poor × Poor |
| Grain yield per plant | IR 79156A × HPR 2720  IR 58025A × HPR 2612  IR 68897A × Koshikari | Average × Good  Good × Poor  Poor × Poor |
| Spikelet fertility | IR 79156A × Naggar Dhan  IR 58025A × HPR 2612  IR 68897A × HPR 2880 | Poor × Poor  Good × Poor  Average × Average |
| 1000-grain weight | IR 58025A × HPR 2612  IR 58025A × Naggar Dhan  IR 68897A × Kasturi | Good × Poor  Good × Poor  Average × Average |
| Grain length | IR 58025A × HPR 2612  IR 79156A × HPR 1156  IR 58025A × RP 2421 | Average × Good  Poor × Average  Average × Good |
| Grain breadth | IR 58025A × HPR 2612  IR 68897A × Koshikari  IR 79156A × HPR 2795 | Poor × Good  Good × Poor  Average × Poor |
| L:B ratio | IR 58025A × HPR 2612  IR 79156A × HPR 1156  IR 68897A × Koshikari | Poor × Good  Poor × Good  Good × Good |

4. Conclusion

The analysis of variance for combining ability explained significant differences among lines for characters *viz.*, plant height at maturity, grain length and L:B ratio and among testers for all the traits except 1000-grain weight, grain length, grain breadth and L:B ratio. Lines × Testers revealed significant differences for all the characters studied which indicated the presence of sufficient amount of variability. Among three lines, IR 58025A stood out as a potential parent due to its possession of good general combining ability for grain yield per plant and majority desirable characters. Among 14 testers, HPR 2143 was found to be good general combiners for 11 characters. These good combiners can be used in future breeding programmes to develop new commercial rice hybrids. IR 58025A × HPR 2612 proved to be the best cross combination as it reflected desirable significant SCA effects for nine traits *viz*., panicle length, spikelets per panicle, grains per panicle, grain yield per plant, spikelet fertility, 1000-grain weight, grain length, grain breadth and L:B ratio, thus, could be exploited further for heterosis breeding. Dominance genetic variance (σ2D) was highly significant as compared to additive genetic variance (σ2A) for all the characters studied which indicated the preponderance of non-additive gene action suggesting the further exploitation of hybrid vigour. The estimates of average degree of dominance (>1) for majority traits under study indicated selection would not be effective for these genotypes since there was preponderance of dominant gene action or non-additive gene action which suggests heterosis breeding would be rewarding. Thus, study revealed the potential parents and superior cross combination which could be further utilized for heterosis breeding. However, Multi-environment trials will be needed across multiple locations, seasons or years to evaluate the true performance of genotypes under diverse environmental conditions.

**DISCLAIMER (ARTIFICIAL INTELLIGENCE)**

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

REFERENCES

Anandalekshmi, L., Geetha, S., Amudha, K., Muthuvijayaragavan, R., & Uma, D. (2020). Combining ability and gene action analysis for yield and yield attributing traits in rice (*Oryza sativa* L.). Electronic Journal of Plant Breeding, 11(3), 901-906.

Anis, G., Hassan, H., El-Sherif, A., Saneoka, H., & EL-Sabagh, A. (2019). Evaluation of new promising rice hybrid and its parental lines for floral, agronomic traits and genetic purity assessment. Pakistan Journal of Agricultural Sciences, 56(3), 567-576.

Azad, A.K., Sarker, U., Ercisli, S., Assouguem, A., Ullah, R., Almeer, R., Sayed, A.A., & Peluso, I. (2022). Evaluation of combining ability and heterosis of popular restorer and male sterile lines for the development of superior rice hybrids. Agronomy, 12(4), 965.

Bradshaw, J.E. (2017). Plant breeding: past, present and future. Euphytica, 213, 60.

Coffman, W.R., & Herrera, R.M. (1980). Rice: hybridization of crop plants. American Society of Agronomy, 9(5), 511-521.

Deepika, K., Manimaran, R., Pushpa, R., Bama, K.S., Umamageswari, C., & Suresh, R. (2023). Studies on variability and heterosis for yield and nutritional traits in rice (*Oryza sativa* L.). Electronic Journal of Plant Breeding, 14 (3), 1135-1146.

Devi, A., Kumari, P., Dwivedi, R., Dwivedi, S., Mishra, K.K., Verma, O.P., Singh, P.K., & Dwivedi, D.K. (2017). Combining ability analysis for yield and its quality traits in rice (*Oryza sativa* L.) over environment. Journal of Pharmacognosy and Phytochemistry, 6(4), 35-42.

El-Namaky, R. (2018). The genetic variability of floral and agronomic characteristics of newly-bred cytoplasmic male sterile rice. Agriculture, 8(5), 68.

El-Shamey, E.A., Sakran, R.M., El-Sayed, M.A., Aloufi, S., Alharthi, B., Alqurashi, M., Mansour, E., & Abd, El-Moneim. D. (2022). Heterosis and combining ability for floral and yield characters in rice using cytoplasmic male sterility system. Saudi Journal of Biological Sciences, 29(5), 3727-3738.

Gramaje, L.V., Caguiat, J.D., Enriquez, J.O.S., delaCruz, Q.D., Millas, R.A., Carampatana, J.E., & Tabanao, D.A. (2020). Heterosis and combining ability analysis in CMS hybrid rice. Euphytica, 216, 1-22.

Hasan, M.J., Kulsum, M.U., Hossain, E., Hossain, M.M., Rahman, M.M., & Rahmat, N.M. (2017). Combining ability analysis for identifying elite parents for heterotic rice hybrids. Academia Journal of Agricultural Research, 3(5), 70-75.

Huang, X., Yang, S., Gong, J., Zhao, Y., Feng, Q., Gong, H., Li, W., Zhan, Q., Cheng, B., Xia, J., & Chen, N. (2015). Genomic analysis of hybrid rice varieties reveals numerous superior alleles that contribute to heterosis. Nature communications, 6(1), 6258.

Hussein, F.A. (2021). Heterosis and combining ability of some coloured rice genotypes for yield characteristics and grain micronutrient content using Line × tester analysis. Journal of Plant Production, 12(6), 635-643.

Kempthorne, O. (1957). An Introduction to Genetic Statistics. John Wiley and Sons, New York, USA, 468-473.

Kirubha, M.A., Gnanamalar, R.P., Thangaraj, K., Pushpam, A.K, & Priyanka, A.R. (2019). Gene action and combining ability studies for protein content and grain quality traits in rice (*Oryza sativa* L.). Electronic Journal of Plant Breeding, 10(1), 58-65.

Krishna, L., Mohan, Y.C., Singh, T.V.J., Kylash, K.S., Prasana, G., Krishna, K., Varma, N.G., & Jagadeeshwar, R. (2024). Deciphering the estimates of combining ability and heterosis for selecting superior parents and hybrids in rice (*Oryza sativa* L.). Electronic Journal of Plant Breeding, 15(3), 689-700.

Kumar, A., & Pandey, D.P. (2023). Study on gene action and combining ability for yield and its component traits in rice for rainfed upland condition in Himachal Pradesh. Himachal Journal of Agricultural Research, 49(1), 38-43.

Kumari, P., Jaiswal, H.K., & Waza, S.A. (2014). Combining ability and heterosis for yield, its component traits and some grain quality parameters in rice (*Oryza sativa* L.). Journal of Applied and Natural Science, 6(2), 495-506.

Lakra, P. (2020). Evaluation of CMS based hybrids for yield and its attributing characters in rice (*Oryza sativa* L.) (Doctoral dissertation, Indira Gandhi Krishi Vishwavidyalaya, Raipur)

Latha, S., Sharma, D., & Sanghera, G.S. (2013). Combining ability and heterosis for grain yield and its component traits in rice (*Oryza sativa* L.). Notulae Scientia Biologicae, 5(1), 90-97.

Liao, C., Yan, W., Chen, Z., Xie, G., Deng, X.W., & Tang, X. (2021). Innovation and development of the third-generation hybrid rice technology. The Crop Journal, 9(3), 693-701.

Nagamani, V., Shivakumar, N., & Nagaraja, T.E. (2022). Estimation of combining ability and heterosis for yield and its component traits for identification of promising red rice (*Oryza sativa* L.) hybrids developed from new WA-based CMS lines and red kernel breeding lines. Electronic Journal of Plant Breeding, 13(1), 146-154.

Nivedha, R., Manonmani, S., Kalaimagal, T., Raveendran, M., & Kavitha, S. (2024). Comprehensive assessment of combining ability and heterosis for the development of superior three-line hybrids in rice (*Oryza sativa* L.). Electronic Journal of Plant Breeding, 15(1), 31-41.

Parimala. K., Bhadru, D., & Raju, C.S. (2018). Combining ability and heterosis studies for grain yield and its components in hybrid rice (*Oryza sativa* L.). Electronic Journal of Plant Breeding, 9(1), 244-255.

Rahimi, M., Rabiei, B., Samizadeh, H., & Kafi, G.A. (2010). Combining ability and heterosis in rice (*Oryza sativa* L.) cultivars. Journal of Agriculture and Scientific Technology, 12, 223 231.

Ramesh, C., Raju, C.D., Raju, C.S., & Varma, N.R. (2018). Combining ability and gene action in hybrid rice. International Journal of Pure and Applied Biosciences, 6(1), 497-510.

Ray, S.R., Islam, A.A., Rasul, M.G., Saikat, M.M.H., & Ahmed, J.U. (2021). Combining ability for yield related traits of Boro rice (*Oryza sativa* L.). Annals of Bangladesh Agriculture, 25(1), 23-31.

Reddy, D.V., Suneetha, Y., & Kumar, B.R. (2024). Combining ability studies of promising restorer lines for yield and yield components in rice (*Oryza sativa* L.). Agriculture Science Digest, 44(3), 460-466.

Saikiran, V., Krishna, L., Mohan, Y.C., & Shankar, V.G. 2018. Identification of heterotic hybrids in rice (*Oryza sativa* L.). Journal of Pharmacognosy and Phytochemistry, 7(5), 3320-3325.

Sala, M., Shanthi, P., & Selvi, B. (2016). Combining ability studies for yield and yield contributing traits in rice (*Oryza sativa* L.). Agricultural Research Journal, 53(1), 13-18.

Saleem, M.Y., Mirza, J.I., & Haq, M.A. (2010). Combining ability analysis for yield and related traits in basmati rice (*Oryza sativa* L.). Pakistan Journal of Botany, 42(1), 627-637.

Salem, T.S., Rabie, H.A., Mowafy, S.A., Eissa, A.E., & Mansour, E. (2020). Combining ability and genetic components of Egyptian cotton for earliness, yield and fiber quality traits. SABRAO Journal of Breeding and Genetics, 52(4), 369-389.

Shrivastav, S.P., Verma, O.P., & Jakhar, D.S. (2024). Estimates of heterosis, inbreeding depression and transgressive segregation in rice (*Oryza sativa* L.) under sodic soil. Research Square, 25(4), 1-9.

Singh, Y., Singh, P.K., Pathak, V.N., Misra, V., Kumar, M., & Mall, A.K. (2019). The estimates of heterobeltiosis and standard heterosis in aerobic rice (*Oryza sativa* L.). Plant Archives, 19(1), 884-888.

Tiwari, A.K., Tiwari, J., Upadhyayi, S., & Sharma, D. (2024). Combining ability analysis for yield and yield contributing traits using cytoplasmic male sterile lines in aromatic hybrids of rice. Plant Archives, 24(1), 649-657.

USDA. 2024. World Agriculture Production. pp: 38

Yousef, M.I., Ghidan, W.F., Talha, I.A., Elsehely, A.B., & Tabl, D.M. (2020). Combining ability, heterosis and gene action for grain yield and its related traits of some WA-CMS with tester lines of rice (*Oryza sativa* L.). Journal of Experimental Agriculture International, 42(9), 102-123.

Yuga, M.E., Kimani, P.M., Olubayo, M.F., Muthomi, J.W., & Nzuve, F.M. (2018). Combining ability of heterosis for agronomic and yield traits in indica and japonica rice crosses. Journal of Agricultural Science, 10(12), 92-103.