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Research Article

Comprehensive assessment of combining ability and heterosis for the development of superior three-line hybrids in rice (*Oryza sativa* L.)

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Abstract
The present study involved assessment of 70 three-line hybrids obtained by crossing five CMS lines and 14 testers using line x tester mating design for combining ability and heterosis for 13 yield and grain quality traits. The Analysis of Variance identified significant difference among crosses and the ratio of GCA and SCA variances were less than unity indicating non-additive gene action for all the traits. The line COMS 24A and testers RNR 15048, WGL 32100, CBSN 504, CBSN 509, CBSN 511 and IR64 DRT were identified as best general combiners through gca effects. Among the hybrids, COMS 24A X WGL 32100, COMS 24A X CBSN 504, COMS 25A X CBSN 511, COMS 25A X CBSN 517, COMS 23A X IR64 DRT and COMS 23A X CBSN 509 demonstrated outstanding sca effects, mean and standard heterosis over CORH 3 and CORH 4. Two hybrids *viz*., COMS 25A X CBSN 511 and COMS 25A X RNR 15048 had medium slender grain type and hold promise for commercial exploitation in south India especially Tamil Nadu.

Keywords: GCA, SCA, three-line hybrid, heterosis, combining ability

INTRODUCTION

Rice, the staple food crop of more than half of the global population is cultivated across an extensive area of 165.25 million hectares (Statista, 2024). However, the march of industrialization has resulted in an annual decline of cultivable land by more than 1% (Rahman *et al*., 2022). Additionally, the challenges posed by climate change in agriculture have escalated the demand for a sustainable increase in rice production, which can be achieved through the development of hybrids. The success of hybrid breeding largely hinges on the judicious selection of parents. The phenotypic performance of parents alone proves to be an unreliable strategy since lines with superior phenotype may not necessarily yield favourable recombination in subsequent generations. Addressing this challenge, combining ability analysis evaluates the potential of parents to pass on genetic information to their progenies thereby facilitating the development of superior hybrids. A line x tester mating design proposed by Kempthrone in 1957 provides insights into heterosis, General Combining Ability (GCA) of parents and Specific Combining Ability (SCA) of hybrids along with the nature of gene action controlling the expression of traits. In this study, 70 hybrid combinations generated by crossing 5 lines and 14 testers using line x tester mating design are evaluated for combining ability and heterosis to identify good combiners among parents and superior hybrid combinations for commercial exploitation.

MATERIALS AND METHODS

The experimental material comprised of five Cytoplasmic Male Sterile (CMS) lines and fourteen testers with diverse origin (**Table 1**). They were crossed in line x tester mating design during *Kharif*, 2022 at Paddy Breeding Station of Tamil Nadu Agricultural University located at 11.0°N, 77.0°E and an elevation of 426.72 meters above sea level. Subsequently, seeds of resulting 70 F_1s along with parents and two hybrid checks (CORH 3 and CORH 4) were raised with a spacing of 30 x 20 cm in a Randomized Block Design with two replications and evaluated during *Rabi*, 2022. All the standard agronomic and intercultural operations were performed throughout the crop season. Thirteen yield and grain quality traits were recorded from five random selected plants of each genotype. During the flowering stage, pollen fertility was assessed by staining pollen from matured anthers of five individual plants with 1% Potassium Iodide solution (Ali *et al*., 2014) and examined under a light microscope (stained pollen (dark blue) – fertile; unstained (colourless) pollen – sterile) and pollen fertility per cent was calculated Subsequently, panicles were covered with butter paper covers to record spikelet fertility at maturity.

Other biometrical traits recorded include days to 50% flowering, plant height, number of productive tillers per plant, panicle length, flag leaf length, flag leaf width, single plant yield, hundred grain weight, grain length, grain breadth and grain length breadth ratio.

Grain type classification: The best performing hybrids were identified and examined for the grain type as per the classification given by IRRI (2002) as follows,

Category (size)	Length (mm)	Category (shape)	Length/breadth (ratio)
Extra long	>7.5	Slender	>3
Long	6.6 – 7.5	Medium	2.1 – 3
Medium	5.51 – 6.6	Bold	1.1 – 2.0
Short	<5.5	Round	<1.1

Statistical analysis: The recorded data for yield and grain characters were subjected to Analysis of Variance following the method suggested by Panse and Sukhatme (1985). The combining ability analysis was conducted using the program 'line x tester with parents' of TNAUSTAT. The general combining ability (gca) of parents and specific combining ability (sca) of hybrids were determined based on the methods given by Kempthorne (1957) and Experiment-II of Comstock and Robinson (1952). Heterobeltiosis and standard heterosis were estimated as per the methods given by Hayes *et al*. (1955) and Singh and Singh (1994).

RESULTS AND DISCUSSION

The Analysis of Variance for combining ability analysis revealed significant difference among the crosses for all the characters under study (**Table 2**). The variance of the cross was partitioned into line, tester and line x tester interactions. All the lines exhibited significant difference for the traits studied, except for flag leaf width. Similarly, testers and line x testers demonstrated significant differences for all the characters, indicating the presence of sufficient variation between parents and crosses. This variation creates an opportunity for heterosis and hybrid vigour across all the characters. The variance of General Combining Ability and Specific Combining Ability indicated that SCA variances were consistently higher than GCA variances for all the yield and grain characters. The ratio between GCA and SCA was less than unity for all the traits signifying the prevalence of non-additive (dominance and epistatic) gene action. The presence of non-additive gene action suggests the potential for exploiting heterosis in the genetic material. A similar pattern of non-additive gene action was reported in previous studies for traits such as plant height, pollen fertility, number of productive tillers per plant, panicle weight, single plant yield and hundred seed weight by Singh and Babu (2012) and Manivelan *et al*. (2022). The proportional contribution of line x tester was observed to be more than the contribution of lines or testers individually for all the characters except flag leaf length (**Fig. 1**). This further confirmed the higher influence of specific combining ability effects for total variation which is in agreement with the findings of Sanghera and Hussain (2012).

The gca effects of parents as presented in **Table 3** serves as a valuable tool for selecting optimal parents in hybrid breeding by leveraging additive gene action. The preferred direction for gca/sca effects was considered positive for traits contributing to yield and negative for traits related to days to 50% flowering (early hybrids), plant height (non-lodging hybrids), and grain breadth (slender grained hybrids). Notably, none of the lines and testers exhibited significance for all the traits simultaneously. Among CMS lines, COMS 24A displayed highly significant positive gca for single plant yield (6.11). This line also had highly

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Table 1. List of lines and tester used for crossing

S. No	Line/ Tester	Name of the genotype	Origin	Subspecies
1	L_1	TNAU CMS 2A	Tamil Nadu	*indica*
2	L_2	COMS 23A	Tamil Nadu	*indica*
3	L_3	COMS 24A	Tamil Nadu	*indica*
4	L_4	COMS 25A	Tamil Nadu	*indica*
5	L_5	COMS 30A	Tamil Nadu	*indica*
6	T_1	CO 51	Tamil Nadu	*indica*
7	T_2	ADT 53	Tamil Nadu	*indica*
8	T_3	ADT 56	Tamil Nadu	*indica*
9	T_4	RNR 15048	Telangana	*indica*
10	T_5	WGL 32100	Telangana	*indica*
11	T_6	CBSN 504	Tamil Nadu	*indica-japonica* cross derivative
12	T_7	CBSN 517	Tamil Nadu	*indica-japonica* cross derivative
13	T_8	CBSN 499	Tamil Nadu	*indica-japonica* cross derivative
14	T_9	CBSN 506	Tamil Nadu	*indica-japonica* cross derivative
15	T_{10}	CBSN 513	Tamil Nadu	*indica-japonica* cross derivative
16	T_{11}	CBSN 511	Tamil Nadu	Wild rice derivative
17	T_{12}	CBSN 509	Tamil Nadu	*indica-japonica* cross derivative
18	T_{13}	CBSN 510	Tamil Nadu	*indica*
19	T_{14}	IR64 DRT	Andhra Pradesh	*indica*

Table 2. ANOVA for combining ability analysis

Source of variation	DF	DFF	PF	SF	PH	NPTPP	PL	FLL	FLW	SPY	HGW	GL	GB	L/B
Replication	1	0.01	0.18	1.05	0.58	34.01	4.26	23.53	0.01	6.28	0.01	0.00	0.00	0.01
Cross	69	118.75^{**}	2156.24^{**}	1741.16^{**}	286.37^{**}	73.14^{*}	13.94^{*}	26.29^{*}	0.03^{*}	402.60^{**}	0.13^{**}	0.01^{**}	0.00^{**}	0.39^{**}
Line	4	476.62^{**}	2183.57^{**}	1580.09^{**}	438.91^{**}	137.32^{**}	21.25^{**}	93.67^{**}	0.03	350.98^{**}	0.15^{**}	0.04^{**}	0.01^{**}	1.24^{**}
Tester	13	134.64^{**}	4914.13^{**}	3639.27^{**}	651.93^{**}	49.82^{*}	21.98^{**}	26.08^{*}	0.03^{*}	699.54^{**}	0.15^{**}	0.02^{**}	0.00^{**}	0.56^{**}
LXT	52	87.25^{**}	1464.67^{**}	1279.02^{**}	183.24^{**}	74.03^{*}	11.37^{*}	21.16^{*}	0.03^{*}	332.34^{**}	0.12^{**}	0.01^{**}	0.00^{**}	0.28^{**}
Error	69	0.49	3.71	3.41	4.52	11.28	4.97	12.32	0.02	2.74	0.02	0.00	0.00	0.00
Total	139	817.75	10722.51	8243.99	1565.56	379.60	77.20	146.16	0.16	1794.47	0.57	0.08	0.01	2.48
σ^2 GCA		0.53	11.60	7.75	1.73	0.01	0.04	0.06	0.00	1.18	0.00	0.00	0.00	0.00
σ^2 SCA		43.38	730.48	637.81	89.36	31.37	3.20	7.72	0.02	164.80	0.05	0.00	0.00	0.14
σ^2 GCA/ σ^2 SCA		0.01	0.02	0.01	0.02	0.00	0.01	0.01	0.00	0.01	0.00	0.03	0.00	0.01

DF – degrees of freedom; DFF- Days to 50% flowering; PF- Pollen Fertility; SF- Spikelet Fertility; PH- Plant Height; NPTPP- Number of Productive Tillers per Plant; PL- Panicle Length; FLL- Flag Leaf Length; FLW- Flag Leaf Width; SPY- Single Plant Yield; HGW- Hundred Grain Weight; GL- Grain Length; GB- Grain Breadth; L/B- Grain Length Breadth ratio

significant positive gca effects for spikelet fertility (4.83), number of productive tillers per plant (3.00), flag leaf length (2.37), hundred grain weight (0.08), grain length (0.04) and grain length breadth ratio (0.06). On the other hand, lines TNAUCMS 2A (-5.69) and COMS 25A (-2.09) demonstrated highly significant negative gca effects for days to 50% flowering. Among the testers, RNR 15048 (9.44), WGL 32100 (12.22), CBSN 504 (2.97), CBSN 513 (5.11), CBSN 511 (10.81), CBSN 509 (6.03) and IR64 DRT (5.03) showed highly significant positive gca effects for single plant yield. Among these, CBSN 511 and IR64 DRT exhibited highly significant positive gca effects for pollen and spikelet fertility, hundred grain weight and grain length. WGL 32100 displayed highly significant positive gca effects for pollen and , spikelet fertility, flag leaf width and desirable negative gca effects for plant height. The

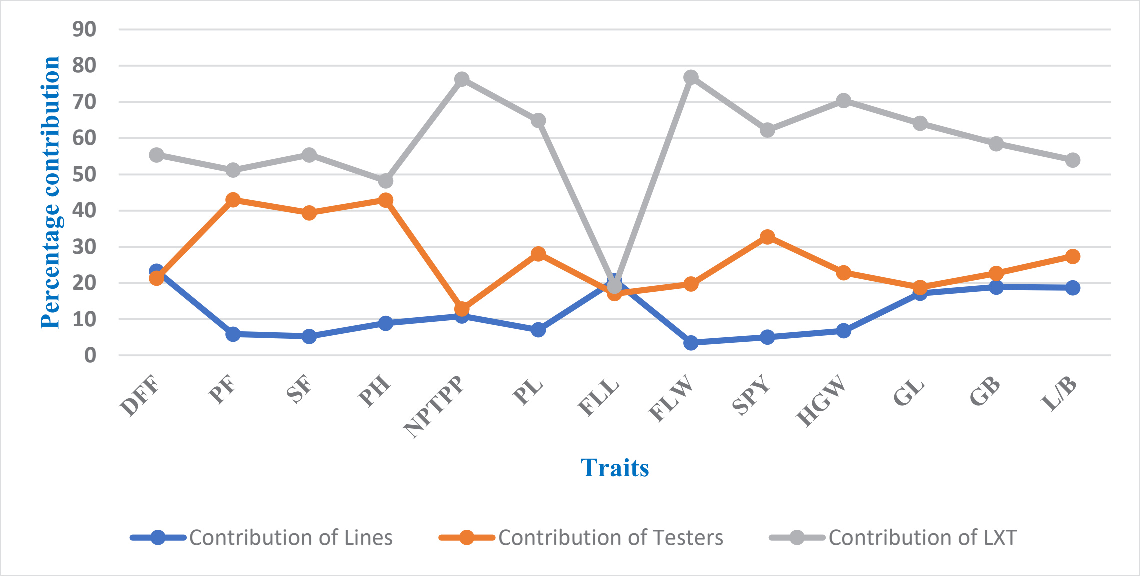

Fig 1. Proportional contribution of lines, testers, line x tester for the total variance

DFF- Days to 50% flowering; PF- Pollen Fertility; SF- Spikelet Fertility; PH- Plant Height; NPTPP- Number of Productive Tillers per Plant; PL- Panicle Length; FLL- Flag Leaf Length; FLW- Flag Leaf Width; SPY- Single Plant Yield; HGW- Hundred Grain Weight; GL- Grain Length; GB- Grain Breadth; L/B- Grain Length Breadth ratio

significant positive gca effects of parents for traits such as pollen fertility, spikelet fertility, grain yield, panicle length, grain length, grain breadth and grain length breadth ratio align with the findings reported by Bhageri and Jeoldar (2010).

The sca effects of hybrids for the yield and grain traits are provided in **Table 4**. None of the cross combinations exhibited desirable and significant sca effects for all the traits simultaneously, consistent with the findings of yuga *et al*. (2018) and Gramaje *et al.* (2020). The significant and desirable negative sca effects for days to 50% flowering were observed in 32 hybrids. For the trait plant height, 23 hybrids had a highly significant negative sca effects. Among 70 hybrids, 30 hybrid combinations demonstrated significant positive sca effects for single plant yield ranging from 2.50 (TNAU CMS 2A X CBSN 504) to 35.88 (COMS 24A X CBSN 517). The hybrid TNAU CMS 2A X ADT 56 displayed highly significant desirable sca effects for days to 50% flowering (-3.01), pollen fertility (27.44), spikelet fertility (17.55), number of productive tillers per plant (7.92), panicle length (2.38) and single plant yield (3.19). Another notable hybrid, COMS 23A X ADT 56 exhibited significant sca effects for days to 50% flowering (-3.61), pollen fertility (10.90), spikelet fertility (19.10), plant height (-5.63), single plant yield (14.41), hundred grain weight (0.31), grain breadth (-0.02) and grain length breadth ratio (0.40). Additional hybrids, including TNAU CMS 2A X CO51, TNAU CMS 2A X CBSN 509, COMS 23A X CBSN 509, COMS 23A X IR64 DRT, COMS 24A X WGL 32100, COMS 24A X CBSN 499, COMS 25A X CBSN 506, COMS 30A X CBSN 510 also exhibited significant desirable sca effects for yield contributing and grain quality traits. The cross combinations with significant negative sca effects for days to 50% flowering and plant height coupled with positive sca effect for other traits were reported in studies by Faiz *et al.* (2006) and Deepika *et al*. (2023). The desirable sca effects of crosses were derived from parents with diverse gca effects. Among 30 hybrids with positive sca effects for yield, 50% were derived from low x high combiners followed by low x low combiners (**Fig. 2**). The high sca of hybrids derived from low x high combiners resulted from both non-additive and additive gene actions by the interaction of recessive and dominant alleles from poor and good combiners respectively. Consequently, such crosses are deemed suitable for heterosis breeding. The heterosis observed in crosses with high x high combiners is attributed to the interaction between positive alleles of both parents, while that from from low x low combiners is due to overdominance/epistasis. Similar findings for low x high and low x low were reported by Rahimi *et al.* (2010) and Reddy *et al*. (2024).

The heterobeltiosis was estimated to compare the generated hybrids with the better parent. Forty-three hybrids for the trait days to 50% flowering and 47 hybrids for the trait plant height exhibited highly significant negative heterobeltiosis. The heterobeltiosis for single plant yield ranged from -93.53 in TNAU CMS 2A X CBSN 517 to 99.64 in COMS 23A X CBSN 509 (**Fig. 3**). The significant positive heterobeltiosis for single plant yield

Table 3. General combining ability effects of parents

Parents	DFF	PF	SF	PH	NPTPP	PL	FLL	FLW	SPY	HGW	GL	GB	L/B
Lines													
L_1	-5.69 ** (87.5**)	-5.12 **	-0.25 ns	-0.50 ns	-0.32 ns	-0.47 ns	-1.37 **	0.0 ns	-0.77 *	0.04 ns	-0.05 **	-0.01 **	-0.04 **
L_2	-0.09 ns	-7.58 **	-6.97 **	-4.46 **	-1.18 ns	-1.16 **	-1.53 **	-0.01 ns	-0.66 *	-0.09 **	0.03 **	-0.02 **	0.33 **
L_3	4.38 **	0.62 ns	4.83 **	6.28 **	3.00 **	0.59 ns	2.37 **	-0.03 ns	6.11 **	0.08 **	0.04 **	0.01 **	0.06 **
L_4	-2.09 **	-2.77 **	-7.50 **	-1.74 **	1.25 ns	0.16 ns	-0.04 ns	-0.01 ns	-3.01 **	0.03 ns	0.01 ns	0.02 **	-0.17 **
L_5	3.49 **	14.84 **	9.88 **	0.42 ns	-2.75 **	0.88 **	0.57 ns	0.05 **	-1.66 **	-0.06 *	-0.03 **	0.01 **	-0.18 **
SE	0.13	0.36	0.35	0.40	0.63	0.42	0.42	0.02	0.31	0.03	0.00	0.00	0.01
Testers													
T_1	-7.04 **	-22.08 **	-17.37 **	-10.97 **	3.66 **	-0.44 ns	-2.84 **	0.02 ns	-6.77 **	0.03 ns	-0.02 **	0.01 **	-0.23 **
T_2	-1.24 **	-26.85 **	-22.78 **	-10.19 **	3.16 **	-0.83 ns	-2.00 **	0.02 ns	-12.49 **	0.07 ns	0.04 **	0.03 **	-0.12 **
T_3	-3.14 **	-24.34 **	-18.50 **	-8.03 **	1.86 ns	-1.20 *	-1.48 *	-0.06 ns	-6.64 **	-0.04 ns	0.07 **	-0.01 **	0.47 **
T_4	3.26 **	20.58 **	23.03 **	0.70 ns	3.56 **	-0.18 ns	1.04 ns	0.07 *	9.44 **	-0.12 *	0.01 ns	-0.02 **	0.29 **
T_5	3.26 **	24.82 **	24.26 **	-4.08 **	0.16 ns	-0.77 ns	0.20 ns	0.11 **	12.22 **	-0.07 ns	-0.03 **	-0.02 **	0.15 **
T_6	2.06 **	-7.42 **	-0.81 ns	3.45 **	-3.04 **	0.12 ns	-0.15 ns	-0.04 ns	2.97 **	-0.06 ns	-0.05 **	-0.01 *	-0.12 **
T_7	-6.94 **	-18.44 **	-16.56 **	1.96 **	-1.34 ns	-0.82 ns	-0.47 ns	-0.04 ns	-9.98 **	0.05 ns	0.03 **	0.00 ns	0.09 **
T_8	-0.54 *	10.41 **	-2.06 **	-6.82 **	-2.74 *	-1.37 **	-0.58 ns	-0.13 **	-8.43 **	0.12 *	0.02 **	0.01 **	-0.06 **
T_9	4.36 **	-29.06 **	-26.16 **	-6.54 **	-0.44 ns	-1.99 **	0.88 ns	-0.03 ns	-6.33 **	-0.26 **	-0.06 **	0.02 **	-0.44 **
T_{10}	-0.24 ns	20.78 **	21.72 **	8.60 **	-0.34 ns	1.57 **	2.22 **	0.03 ns	5.11 **	-0.02 ns	-0.06 **	-0.01 **	-0.13 **
T_{11}	1.26 **	16.72 **	17.24 **	7.53 **	-0.64 ns	0.39 ns	2.33 **	-0.07 *	10.81 **	0.17 **	0.02 **	-0.00 *	0.11 **
T_{12}	3.16 **	30.53 **	21.50 **	10.35 **	-1.94 ns	1.17 *	1.66 *	0.00 ns	6.03 **	0.03 ns	0.02 **	0.00 ns	0.08 **
T_{13}	-1.14 **	-14.39 **	-12.90 **	14.10 **	-1.34 ns	4.08 **	0.49 ns	0.06 ns	-0.98 ns	-0.11 *	-0.05 **	0.00 ns	-0.23 **
T_{14}	2.86 **	18.69 **	9.40 **	-0.06 ns	-0.64 ns	0.25 ns	-1.32 ns	0.06 ns	5.03 **	0.21 **	0.06 **	0.00 ns	0.15 **
SE	0.22	0.61	0.58	0.67	1.06	0.71	0.71	0.03	0.52	0.05	0.01	0.00	0.02

*significant at p=0.05 level; **significant at p=0.01 level

DF – degrees of freedom; DFF- Days to 50% flowering; PF- Pollen Fertility; SF- Spikelet Fertility; PH- Plant Height; NPTPP- Number of Productive Tillers per Plant; PL- Panicle Length; FLL- Flag Leaf Length; FLW- Flag Leaf Width; SPY- Single Plant Yield; HGW- Hundred Grain Weight; GL- Grain Length; GB- Grain Breadth; L/B- Grain Length Breadth ratio

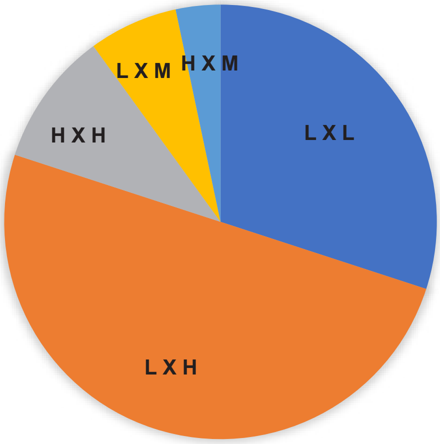

Fig. 2. Combination of parents with different gca effects yielding superior sca effects of hybrids for single plant yield

L – Low gca effect; M- Medium gcs effect; H – High gca effect

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Table 4. SCA effects of hybrids

	DFF	PF	SF	PH	NPTPP	PL	FLL	FLW	SPY	HGW	GL	GB	L/B
L_1XT_1	-2.11 **	31.68 **	31.96 **	-4.31 **	-0.38 ns	-7.31 **	-0.20 ns	-0.11 ns	13.95 **	-0.23 *	-0.01 ns	0.01 *	-0.17 **
L_1XT_2	1.09 *	-14.55 **	-15.12 **	12.91 **	9.12 **	0.08 ns	-3.54 *	0.02 ns	-2.46 *	-0.14 ns	0.05 **	-0.00 ns	0.16 **
L_1XT_3	-3.01 **	27.44 **	17.55 **	5.42 **	7.92 **	2.38 *	-1.06 ns	0.07 ns	3.19 **	0.02 ns	0.01 ns	0.04 **	-0.46 **
L_1XT_4	8.09 **	16.02 **	9.47 **	-0.93 ns	1.22 ns	-0.32 ns	-0.87 ns	-0.13 ns	4.45 **	0.20 ns	0.10 **	-0.01 ns	0.57 **
L_1XT_5	-4.41 **	6.53 **	1.84 ns	-0.03 ns	6.62 **	0.77 ns	2.26 ns	0.05 ns	2.57 *	0.13 ns	-0.01 ns	0.01 **	-0.20 **
L_1XT_6	4.79 **	1.52 ns	-4.74 **	-13.90 **	-2.68 ns	0.27 ns	-0.89 ns	0.27 **	2.50 *	-0.21 *	-0.00 ns	0.01 ns	-0.12 **
L_1XT_7	-3.21 **	-40.01 **	-41.44 **	6.30 **	-4.38 ns	1.40 ns	1.93 ns	0.09 ns	-13.23 **	-0.11 ns	-0.04 **	0.00 ns	-0.19 **
L_1XT_8	-4.11 **	-27.66 **	-7.69 **	-6.31 **	-6.48 **	1.74 ns	-3.70 *	-0.00 ns	2.06 ns	0.04 ns	0.07 **	0.01 ns	0.11 **
L_1XT_9	2.99 **	-27.74 **	-32.89 **	-7.04 **	0.72 ns	-1.14 ns	1.33 ns	-0.13 *	-15.12 **	-0.11 ns	-0.03 *	-0.00 ns	-0.08 *
L_1XT_{10}	-4.91 **	5.82 *	4.83 **	-8.15 **	-3.38 ns	-1.16 ns	-2.92 ns	0.03 ns	-3.94 **	0.10 ns	0.05 **	-0.03 **	0.61 **
L_1XT_{11}	-5.41 **	15.33 *	7.06 **	0.73 ns	-0.58 ns	0.85 ns	1.00 ns	0.08 ns	-3.36 **	-0.02 ns	-0.07 **	-0.00 ns	-0.22 **
L_1XT_{12}	-1.31 **	6.57 *	13.59 **	3.37 *	1.72 ns	-2.24 ns	2.39 ns	-0.05 ns	6.08 **	0.01 ns	-0.04 *	-0.01 *	0.01 ns
L_1XT_{13}	8.99 **	6.99 *	-5.75 **	11.87 **	-6.38 **	1.17 ns	2.47 ns	-0.09 ns	7.91 **	0.03 ns	-0.04 **	-0.03 **	0.16 **
L_1XT_{14}	2.49 **	-7.89 *	21.35 **	0.08 ns	-3.08 ns	3.50 **	1.78 ns	-0.10 ns	-4.60 **	0.30 **	-0.04 **	0.00 ns	-0.20 **
L_2XT_1	-4.71 **	-32.16 **	-32.22 **	4.28 **	-4.52 ns	1.71 ns	1.12 ns	0.02 ns	-13.27 **	0.05 ns	-0.11 **	-0.02 **	-0.19 **
L_2XT_2	-8.51 **	-20.69 **	-17.28 **	-4.13 **	0.48 ns	0.85 ns	-0.88 ns	0.06 ns	-10.18 **	-0.28 **	0.05 **	-0.04 **	0.61 **
L_2XT_3	-3.61 **	10.90 **	19.10 **	-5.63 **	2.28 ns	0.75 ns	0.93 ns	-0.08 ns	14.14 **	0.31 **	0.02 ns	-0.02 **	0.40 **
L_2XT_4	-11.51 **	19.18 **	15.84 **	5.98 **	-0.92 ns	2.36 *	0.42 ns	0.07 ns	3.47 **	0.01 ns	0.05 **	-0.01 ns	0.33 **
L_2XT_5	5.49 **	2.89 *	12.91 **	-2.58 ns	5.48 *	0.21 ns	-1.77 ns	-0.18 **	6.29 **	0.04 ns	-0.04 *	0.02 **	-0.38 **
L_2XT_6	-6.31 **	-21.52 **	-18.77 **	-0.62 ns	0.18 ns	-0.93 ns	-2.90 ns	0.07 ns	-8.90 **	-0.05 ns	-0.06 **	0.00 ns	-0.27 **
L_2XT_7	-6.31 **	53.00 **	45.18 **	-4.88 **	-11.02 **	-0.25 ns	-4.91 **	0.02 ns	-8.49 **	-0.19 ns	-0.05 **	-0.01 *	-0.10 **
L_2XT_8	13.79 **	-6.35 **	-5.56 **	-0.67 ns	-0.62 ns	0.52 ns	0.20 ns	-0.05 ns	-3.75 **	-0.04 ns	-0.04 **	-0.04 **	0.31 **
L_2XT_9	-0.11 ns	-18.58 **	-18.52 **	2.22 ns	-2.42 ns	-3.58 **	-2.26 ns	0.06 ns	7.89 **	0.05 ns	0.02 ns	0.03 **	-0.27 **
L_2XT_{10}	6.49 **	14.78 *	15.75 **	-0.92 ns	-2.52 ns	1.40 ns	4.40 **	-0.00 ns	8.79 **	0.13 ns	-0.01 ns	0.03 **	-0.50 **
L_2XT_{11}	-1.01 *	-32.66 *	-21.87 **	1.82 ns	-0.22 ns	0.96 ns	-1.21 ns	-0.12 ns	-21.14 **	-0.08 ns	0.08 **	-0.01 ns	0.40 **
L_2XT_{12}	8.59 **	9.53 *	-24.63 **	-12.68 **	4.08 ns	-1.24 ns	-3.54 *	0.08 ns	10.35 **	-0.45 **	0.08 **	-0.02 **	0.56 **
L_2XT_{13}	6.39 **	0.45 n	5.47 **	3.57 *	14.48 **	1.55 ns	2.98 ns	-0.13 ns	-4.95 **	0.12 ns	-0.06 **	0.05 **	-0.79 **
L_2XT_{14}	1.39 **	21.22 *	24.62 **	14.24 **	-4.72 *	-4.32 **	7.44 **	0.19 **	19.76 **	0.37 **	0.05 **	0.02 **	-0.10 **
L_3XT_1	3.82 **	4.44 **	4.45 **	0.41 ns	4.80 *	2.73 *	1.54 ns	-0.04 ns	-4.23 **	0.31 **	0.18 **	0.01 *	0.50 **
L_3XT_2	-0.98 *	7.71 **	3.17 *	-4.20 **	-3.70 ns	2.97 *	5.18 **	-0.01 ns	-1.67 ns	0.26 *	-0.02 ns	0.02 **	-0.33 **
L_3XT_3	-0.08 ns	-31.90 **	-33.93 **	0.39 ns	-3.90 ns	-0.62 ns	3.61 *	0.06 ns	-19.41 **	-0.04 ns	-0.03 *	-0.02 **	0.13 **
L_3XT_4	0.02 ns	-8.72 **	-8.01 **	-0.75 ns	0.40 ns	-0.97 ns	-2.32 ns	0.18 **	-4.55 **	-0.07 ns	-0.01 ns	0.01 *	-0.23 **
L_3XT_5	-4.98 **	3.04 *	1.96 ns	3.19 *	-6.70 **	1.46 ns	-2.23 ns	0.11 ns	7.28 **	0.24 *	0.07 **	0.00 ns	0.21 **
L_3XT_6	-2.28 **	28.28 **	22.53 **	33.99 **	0.00 ns	2.23 ns	5.20 **	-0.26 **	8.32 **	0.23 *	0.00 ns	0.03 **	-0.36 **
L_3XT_7	-3.78 **	-46.35 **	-35.92 **	-4.76 **	19.80 **	-6.01 **	4.69 **	-0.01 ns	-12.46 **	-0.17 ns	0.05 **	-0.04 **	0.74 **
L_3XT_8	-6.18 **	10.45 **	14.35 **	-12.41 **	3.70 ns	-0.01 ns	0.80 ns	-0.18 **	4.48 **	0.22 *	0.04 *	-0.00 ns	0.10 **
L_3XT_9	-2.08 **	6.42 **	17.70 **	-0.36 ns	2.90 ns	1.73 ns	-0.36 ns	-0.19 **	1.63 ns	0.05 ns	-0.02 ns	-0.01 ns	0.04 ns
L_3XT_{10}	-2.48 **	10.08 *	-2.70 *	-0.16 ns	4.30 ns	0.55 ns	-1.84 ns	0.12 ns	0.85 ns	-0.13 ns	-0.06 **	0.00 ns	-0.26 **
L_3XT_{11}	19.52 **	3.64 *	2.98 *	5.92 **	2.60 ns	-0.95 ns	-1.11 ns	0.00 ns	17.44 **	-0.14 ns	-0.08 **	-0.01 ns	-0.21 **
L_3XT_{12}	-0.38 ns	-5.97 *	-2.29 ns	1.59 ns	-10.60 **	0.51 ns	-2.94 ns	0.15 *	-5.98 **	-0.04 ns	-0.04 **	0.02 **	-0.42 **
L_3XT_{13}	2.42 **	8.95 *	4.07 **	-18.16 **	-12.70 **	-2.56 *	-3.77 *	0.11 ns	8.70 **	-0.33 **	-0.08 **	-0.03 **	0.02 ns
L_3XT_{14}	-2.58 **	9.97 *	11.67 **	-4.70 **	-0.90 ns	-1.07 ns	-6.46 **	-0.04 ns	-0.43 ns	-0.39 **	0.02 ns	-0.00 ns	0.09 *
L_4XT_1	-6.21 **	-40.18 **	-31.93 **	2.34 ns	-5.95 *	0.02 ns	-3.83 *	-0.13 ns	-11.54 **	0.02 ns	-0.02 ns	-0.00 ns	-0.01 ns
L_4XT_2	2.49 **	-6.90 **	-8.81 **	-6.52 **	-5.45 *	-3.39 **	-0.54 ns	-0.16 *	-3.99 **	-0.21 *	-0.06 **	-0.02 **	0.00 ns
L_4XT_3	4.89 **	-29.41 **	-22.01 **	0.49 ns	-3.15 ns	-2.94 *	-0.15 ns	-0.12 ns	-6.99 **	0.02 ns	0.02 ns	-0.00 ns	0.05 ns
L_4XT_4	0.49 ns	0.97 ns	10.32 **	-8.24 **	-2.35 ns	-0.21 ns	2.59 ns	0.15 *	10.09 **	0.16 ns	-0.08 **	-0.02 **	-0.09 **

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Table 4. Continued..

	DFF	PF	SF	PH	NPTPP	PL	FLL	FLW	SPY	HGW	GL	GB	L/B
L_4XT_5	5.49 **	-4.27 **	1.04 ns	-6.96 **	-3.45 ns	-2.11 ns	0.92 ns	-0.08 ns	-5.94 **	0.15 ns	0.08 **	0.02 **	0.03 ns
L_4XT_6	2.69 **	33.17 **	30.46 **	-5.83 **	-0.25 ns	-0.25 ns	1.27 ns	-0.12 ns	15.27 **	0.10 ns	0.03 *	0.00 ns	0.07 *
L_4XT_7	8.69 **	50.79 **	48.66 **	1.50 ns	-0.45 ns	4.13 **	-1.20 ns	0.03 ns	35.88 **	0.37 **	0.05 **	0.04 **	-0.30 **
L_4XT_8	-0.71 ns	15.84 **	-21.10 **	19.77 **	3.45 ns	0.98 ns	2.21 ns	0.16 *	0.85 ns	-0.17 ns	-0.01 ns	0.00 ns	-0.06 ns
L_4XT_9	-0.11 ns	53.76 **	38.15 **	-3.50 *	0.15 ns	1.10 ns	3.99 *	0.08 ns	8.57 **	0.02 ns	0.04 **	-0.02 **	0.40 **
L_4XT_{10}	1.49 **	-23.53 *	-12.12 **	3.36 *	-1.45 ns	-0.96 ns	-1.60 ns	-0.10 ns	-16.19 **	0.02 ns	0.01 ns	0.00 ns	0.00 ns
L_4XT_{11}	-8.01 **	14.33 *	17.61 **	-10.07 **	2.35 ns	-2.52 *	-2.20 ns	-0.01 ns	19.71 **	-0.03 ns	-0.00 ns	0.00 ns	-0.05 ns
L_4XT_{12}	-1.91 **	3.72 *	22.11 **	4.27 **	8.15 **	0.74 ns	-2.03 ns	-0.14 *	-9.57 **	0.02 ns	-0.01 ns	-0.00 ns	-0.02 ns
L_4XT_{13}	-14.61 **	-47.81 *	-36.65 **	17.86 **	4.05 ns	5.03 **	1.13 ns	0.22 **	-18.30 **	-0.02 ns	0.04 *	0.01 **	-0.00 ns
L4XT$_{14}$	5.39 **	-20.44 *	-35.71 **	-8.48 **	4.35 ns	0.36 ns	-0.55 ns	0.22 **	-17.86 **	-0.44 **	-0.09 **	-0.02 **	-0.03 ns
L_5XT_1	9.21 **	36.22 **	27.74 **	-2.73 ns	6.05 *	2.84 *	1.36 ns	0.25 **	15.09 **	-0.14 ns	-0.04 **	-0.00 ns	-0.13 **
L_5XT_2	5.91 **	34.44 **	38.05 **	1.94 ns	-0.45 ns	-0.52 ns	-0.23 ns	0.10 ns	18.30 **	0.37 **	-0.01 ns	0.04 **	-0.44 **
L_5XT_3	1.81 **	22.98 **	19.29 **	-0.67 ns	-3.15 ns	0.43 ns	-3.34 *	0.06 ns	9.07 **	-0.31 **	-0.02 ns	-0.00 ns	-0.13 **
L_5XT_4	2.91 **	-27.44 **	-27.61 **	3.94 *	1.65 ns	-0.86 ns	0.19 ns	-0.27 **	-13.45 **	-0.29 **	-0.06 **	0.03 **	-0.58 **
L_5XT_5	-1.59 **	-8.18 **	-17.75 **	6.38 **	-1.95 ns	-0.33 ns	0.82 ns	0.11 ns	-10.21 **	-0.56 **	-0.10 **	-0.06 **	0.33 **
L_5XT_6	1.11 *	-41.44 **	-29.47 **	-13.65 **	2.75 ns	-1.31 ns	-2.68 ns	0.03 ns	-17.20 **	-0.08 ns	0.02 ns	-0.05 **	0.67 **
L_5XT_7	4.61 **	-17.42 **	-16.47 **	1.84 ns	-3.95 ns	0.72 ns	-0.51 ns	-0.14 *	-1.71 ns	0.11 ns	-0.00 ns	0.01 ns	-0.14 **
L_5XT_8	-2.79 **	7.73 **	20.00 **	-0.38 ns	-0.05 ns	-3.24 **	0.48 ns	0.08 ns	-3.64 **	-0.06 ns	-0.05 **	0.03 **	-0.46 **
L_5XT_9	-0.69 ns	-13.85 **	-4.44 **	8.68 **	-1.35 ns	1.88 ns	-2.70 ns	0.19 **	-2.97 *	-0.01 ns	-0.01 ns	0.01 ns	-0.09 *
L_5XT_{10}	-0.59 ns	-7.14 *	-5.75 **	5.87 **	3.05 ns	0.16 ns	1.96 ns	-0.05 ns	10.49 **	-0.12 ns	0.01 ns	-0.01 *	0.15 **
L_5XT_{11}	-5.09 **	-0.63 n	-5.77 **	1.61 ns	-4.15 ns	1.67 ns	3.53 *	0.05 ns	-12.66 **	0.27 **	0.07 **	0.01 *	0.08 *
L_5XT_{12}	-4.99 **	-13.84 *	-8.78 **	3.45 *	-3.35 ns	2.22 ns	6.12 **	-0.03 ns	-0.88 ns	0.46 **	0.00 ns	0.01 ns	-0.12 **
L_5XT_{13}	-3.19 **	31.43 *	32.87 **	-15.14 **	0.55 ns	-5.19 **	-2.81 ns	-0.10 ns	6.64 **	0.20 ns	0.13 **	-0.01 *	0.60 **
L_5XT_{14}	-6.69 **	-2.85 *	-21.92 **	-1.14 ns	4.35 ns	1.53 ns	-2.21 ns	-0.27 **	3.12 **	0.16 ns	0.07 **	-0.00 ns	0.24 **

*significant at p=0.05 level; **significant at p=0.01 level

DF – degrees of freedom; DFF- Days to 50% flowering; PF- Pollen Fertility; SF- Spikelet Fertility; PH- Plant Height; NPTPP- Number of Productive Tillers per Plant; PL- Panicle Length; FLL- Flag Leaf Length; FLW- Flag Leaf Width; SPY- Single Plant Yield; HGW- Hundred Grain Weight; GL- Grain Length; GB- Grain Breadth; L/B- Grain Length Breadth ratio

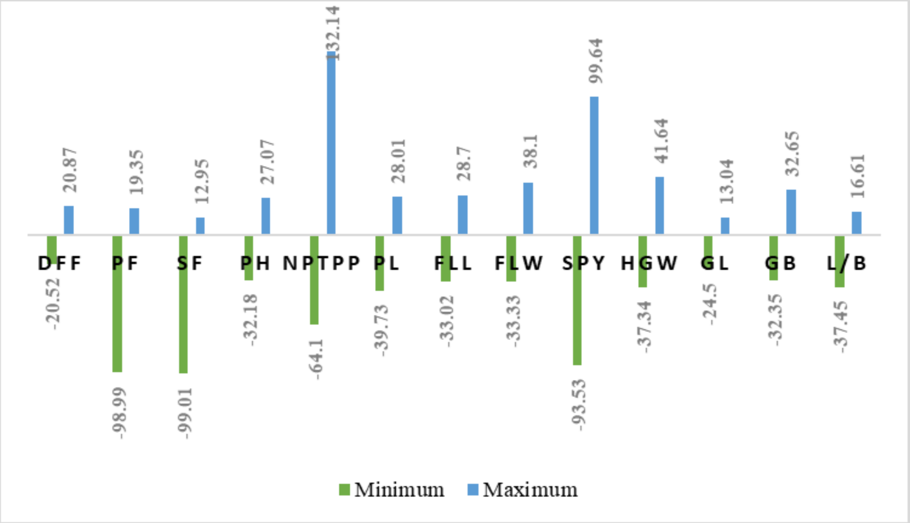

Fig. 3. Range of heterobeltiosis for yield and grain characters in hybrids

were observed for thirteen hybrids among which COMS 23A X CBSN 509 (99.64), COMS 24A X CBSN 517 (86.52), COMS 23A X CBSN 513 (57.77) and COMS 24A X CBSN 511 (54.59) notably had high heterobeltiosis. Among these thirteen hybrids, TNAU CMS 2A X CBSN 509 possessed positive heterobeltiosis for pollen fertility, spikelet fertility and negative heterbeltiosis for plant height. Similarly, the hybrid COMS 25A X CBSN 517 had desirable heterobeltiosis for pollen fertility, plant height and hundred grain weight. Azad *et al*. (2022) also reported negative heterobeltiosis for plant height which is desirable for developing short duration hybrids.

The standard heterosis was estimated to assess the performance of hybrids using two checks, namely, CORH 3 for short duration and CORH 4 for medium duration (**Fig. 4, 5**). Among 70 hybrids, for the trait single plant yield, COMS 23A X IR64 DRT (32.57, 15.62), COMS 24A

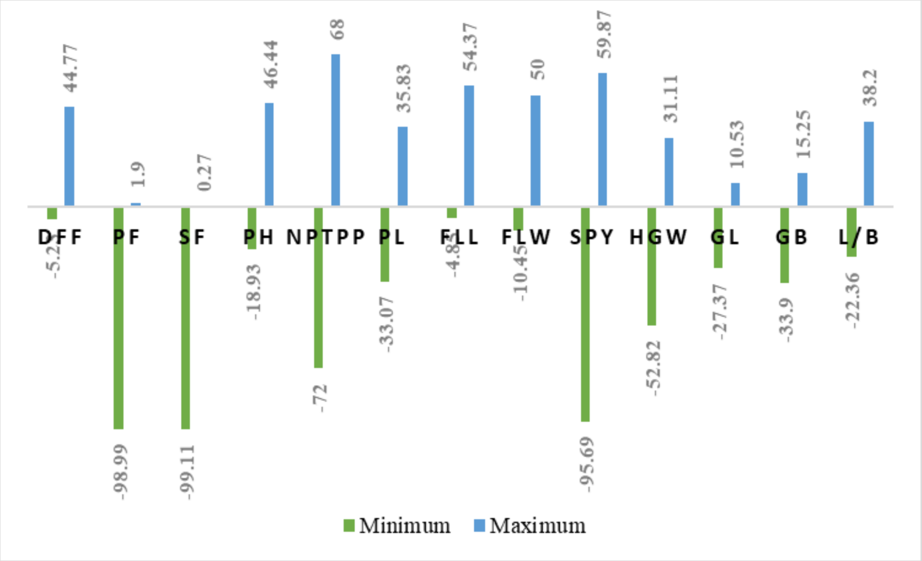

Fig. 4. Range of Standard heterosis against CORH 3 for yield and grain characters in hybrids

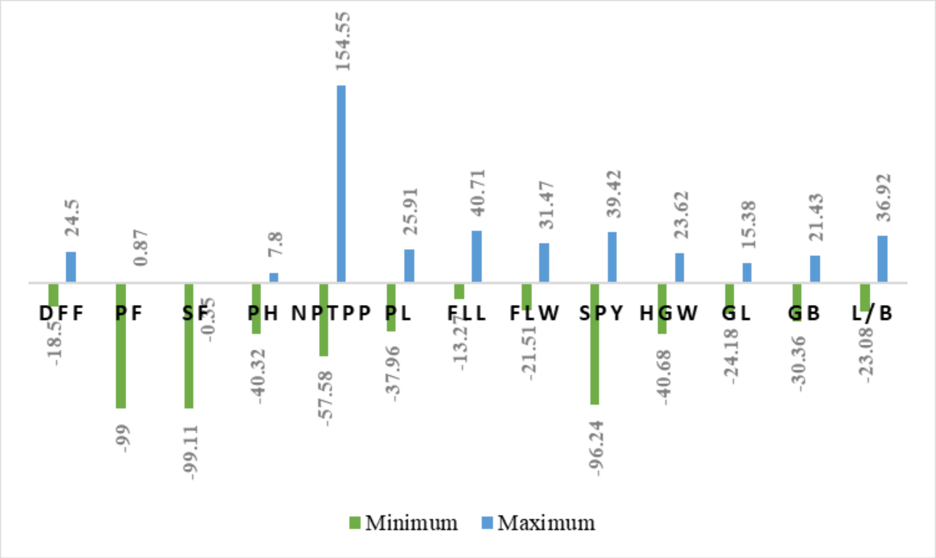

Fig. 5. Range of Standard heterosis against CORH 4 for yield and grain characters in hybrids

DFF- Days to 50% flowering; PF- Pollen Fertility; SF- Spikelet Fertility; PH- Plant Height; NPTPP- Number of Productive Tillers per Plant; PL- Panicle Length; FLL- Flag Leaf Length; FLW- Flag Leaf Width; SPY- Single Plant Yield; HGW- Hundred Grain Weight; GL- Grain Length; GB- Grain Breadth; L/B- Grain Length Breadth ratio

X WGL 32100 (36.53, 19.07), COMS 24A X CBSN 511 (59.87, 39.42), COMS 25A X CBSN 517 (9.29, 12.76) and COMS 25A X CBSN 511 (41.60, 23.49) demonstrated highly significant positive heterosis over both the checks CORH3 and CORH4 (**Table 5**). Four hybrids *viz*., COMS 23A X CBSN 509 (10.17), COMS 23A X WGL 32100 (15.87), COMS 24A X CBSN 504 (14.63), COMS 25A X RNR 15048 (12.27) and COMS 25A X CBSN 504 (8.84) were heterotic over CORH 3 for yield. The hybrids with significant negative heterosis over both checks for days to 50% flowering were TNAU CMS 2A X CO 51 (-1.74, -15.50), TNAU CMS 2A X CBSN 517 (-2.91, -16.50), COMS 25A X CO 51 (-2.33, -16.00) and COMS 25A X CBSN 510 (-5.23, -18.50). These combinations can be instrumental in developing short duration hybrids. Apart from yield, COMS 25A X CBSN 511 showed standard heterosis in desirable direction for days to 50% flowering (-9.50), plant height (-29.16), number of productive tillers per plant (42.42) and grain length breadth ratio (-3.85) over the check CORH 4. The hybrid COMS 23A X IR64 DRT exhibited standard heterosis for plant height (-18.38) and hundred seed weight (20.73) over CORH 4, along with standard heterosis for flag leaf length (39.81, 27.43), flag leaf width (43.18, 25.50), grain length (4.74, 9.34) and grain length breadth ratio (12.42, 11.38) over both hybrid checks. The discussed cross combinations were high-yielding, short duration and semi-dwarf. The semi-dwarf nature of plant is much desirable to withstand lodging in rice crop which can be attained in the above hybrid cross combinations.

Based on significant mean, gca effects of parents, sca effects of hybrids, heterobeltiosis and standard heterosis for yield and contributing traits, among 70 hybrid combinations, the top ten hybrids namely COMS 24A X WGL 32100, COMS 24A X CBSN 504, COMS 25A X RNR 15048, COMS 25A X CBSN 511, COMS 25A X CBSN 517, COMS 23A X IR64 DRT, COMS 23A X CBSN 509, COMS 24A X CBSN 511, COMS 23A X WGL 32100 and COMS 25A X CBSN 504 were identified. The grains of these hybrids were classified according to IRRI classification (2002) based on kernel length and kernel length breadth ratio (**Table 6**). Five hybrids belonged to long slender grain type which were derived from *indica-japonica* derivatives, wild rice magic derivative, WGL 32100 and IR64 DRT. The F$_1$s of cross between the CMS line COMS 25A and testers CBSN 511 and RNR 15048 produced medium slender grains which are much preferred for consumption in south Indian market especially Tamil Nadu. Hence the cross COMS 25A X CBSN 511 can be released as short duration hybrid since it has high yield, medium slender grains with significant mean and desired sca effects for days to 50% flowering.

In conclusion, the ratio of GCA and SCA variances put forth the occurrence of non-additive gene action for all the traits under study. Based on general combining ability effects, the line COMS 24A and testers RNR 15048, WGL 32100, CBSN 504, CBSN 509, CBSN 511 and IR64 DRT stood out as the best combiners. Most of the superior hybrids were derived from crossing between parents with low x high gca effects. The significant sca effects, mean, heterobeltiosis and standard heterosis for yield and grain quality traits identified COMS 25A X CBSN 511 and COMS 25A X RNR 15048 as promising short and medium duration hybrids respectively and can be recommended for multilocation or multi-season testing for commercial exploitation.

Table 5. Details of best hybrids

S. No.	Hybrids	Single plant yield					Desirable sca effects for other traits	gca effect of parents for single plant yield
		Mean	sca effect	Hetero-beltiosis	Standard heterosis			
					CORH 3	CORH 4		
1	COMS 24A X WGL 32100	51.20**	7.28**	10.11**	36.53**	19.07**	DFF, PF, HGW, GL, L/B	H x H
2	COMS 24A X CBSN 504	42.98**	8.32**	-15.69**	14.63**	-0.03 ns	DFF, PF, SF, FLL, HGW	H x H
3	COMS 25A X CBSN 511	53.10**	19.71**	36.93**	41.60**	23.49**	DFF, PF, SF, PH	L x H
4	COMS 25A X CBSN 517	48.48**	35.88**	86.52**	29.29**	12.76**	PF, SF, PL, GL	L x L
5	COMS 23A X IR64 DRT	49.72**	19.76**	35.22**	32.57**	15.62**	PF, SF, FLL, FLW, HGW, GL	L x H
6	COMS 23A X CBSN 509	41.32**	10.35**	99.64**	10.17**	-3.92 ns	PF, PH, GL, GB, L/B	L x H
7	COMS 24A X CBSN 511	59.95**	17.44**	54.59**	59.87**	39.42**	PF, SF	H x H
8	COMS 23A X WGL 32100	43.45	6.29**	-6.56 ns	15.87**	1.05 ns	PF, SF, NPTPP	L x H
9	COMS 25A X CBSN 504	40.82**	15.27**	-19.95**	8.84**	-5.04 ns	PH, PF, SF, GL, L/B	L x H
10	COMS 25A X RNR 15048	42.10**	10.09**	-21.40**	12.27**	-2.09 ns	SF, PH, FLW, GB	L x H

DF – degrees of freedom; DFF- Days to 50% flowering; PF- Pollen Fertility; SF- Spikelet Fertility; PH- Plant Height; NPTPP- Number of Productive Tillers per Plant; PL- Panicle Length; FLL- Flag Leaf Length; FLW- Flag Leaf Width; SPY- Single Plant Yield; HGW- Hundred Grain Weight; GL- Grain Length; GB- Grain Breadth; L/B- Grain Length Breadth ratio

Table 6. Grain type classification of best hybrids according to IRRI (2002)

S. No	Hybrid	Kernel length	Kernel breadth	Kernel length breadth ratio	Grain type
1	COMS 24A X WGL 32100	0.72	0.22	3.27	LS
2	COMS 24A X CBSN 504	0.60	0.24	2.50	MM
3	COMS 25A X CBSN 511	0.65	0.21	3.10	MS
4	COMS 25A X CBSN 517	0.72	0.24	3.00	LS
5	COMS 23A X IR64 DRT	0.72	0.20	3.60	LS
6	COMS 23A X CBSN 509	0.72	0.20	3.62	LS
7	COMS 24A X CBSN 511	0.62	0.24	2.58	MM
8	COMS 23A X WGL 32100	0.60	0.20	3.00	MM
9	COMS 25A X CBSN 504	0.67	0.20	3.33	LS
10	COMS 25A X RNR 15048	0.64	0.21	3.05	MS
11	CORH3	0.66	0.22	3.00	MS
12	CORH4	0.66	0.22	3.00	MS

LS – Long Slender; MM – Medium Medium; MS – Medium Slender

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