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Research article

Combining ability test of parental lines for three-line hybrid rice breeding

Anuchita Rattanarat[a], Thanakorn Wangsawang[a,b], Weerachai Matthayathaworn[a], Ronnachai Changsri[c], Fisseha Worede[d], Khin Sandar Cho[e], Tanee Sreewongchai[a,*], Prapa Sripichitt[a]

[a] *Department of Agronomy, Faculty of Agriculture, Kasetsart University, Bangkok 10900, Thailand.*
[b] *Faculty of Agricultural Technology, Valaya Alongkorn Rajabhat University under the Royal Patronage, Pathum Thani 13180, Thailand.*
[c] *Chumphae Rice Research Center, Rice Department, Ministry of Agriculture and Cooperatives, Khonkaen 40130, Thailand.*
[d] *Amhara Regional Agricultural Research Institute, Sirinka Agricultural Research Center, Bahia Dar, Ethiopia.*
[e] *New Plant Variety Protection Section, Department of Agricultural Research, Yezin, Naypyitaw, Myanmar.*

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Abstract

Information on combining ability and heterosis is important for choosing parental lines in a hybrid rice breeding program. The combining ability of parental lines was evaluated using 4 A-lines and 20 R-lines from different cooking quality groups to select superior genotypes. In total, 40 F_1 crosses were planted in the field in a randomized complete block design. The results indicated that the R-lines of KUR8-14-2 (low amylose with aroma) and KUR7-238 (high amylose) had high general combining ability with values of 4.32 and 6.56, respectively. Accordingly, KUA3 of the A-line from the low amylose with aroma group and KUA2 with high amylose had high GCA values of 1.05 and 2.20, respectively. The highest specific combining ability was in crosses between KUA3 and KUR8-11-8 in the low amylose with aroma group and between KUA8 and KUR9-271 in the high amylose group with values of 9.99 and 3.41, respectively. The crosses between KUA3 and KUR8-11-8 in the low amylose with aroma group and between KUA2 and KUR7-238 in the high amylose group showed high standard heterosis (170.25% and 109.33%, respectively) compared to the commercial varieties RD49 (pure line variety) and RDH1 (hybrid variety) with values of 119.46% and 69.88%, respectively. These parental lines can be used to produce future F_1 hybrid rice varieties on a commercial scale.

Introduction

Rice (*Oryza sativa* L.) has been one of the most major stable food crops in the world (Khush, 2005. The world population is increasing, but the production and productivity of rice is reducing (Khush, 2005). Consequently, technological development that results in a higher grain yield of rice is essential to satisfy the growing global demand (Akhter et al., 2007; Qin et al., 2013). Hybrid rice is one of the agricultural technologies used to increase productivity, being 15%–20% higher yielding than inbred or commercial varieties (Virmani et al., 1997). The limitation of hybrid rice production is that rice is a self-pollinated plant, so that hybrid rice development requires male sterility. A three-line hybrid rice system includes an A-line (male sterility controlled by genes in the cytoplasm and the nucleus), a B-line (maintainer line planted to expand the A-line for creating hybrids) and an R-line (fertility restorer line used as male fertile by crossing with the A-line) (Virmani et al., 1997). Heterosis utilization has been a main tactic to increase plant productivity, particularly in rice, to meet the ever-increasing demand to feed the global population from a reducing area of arable land (Masood et al., 2005). The different

* Corresponding author.
E-mail address: agrtns@ku.ac.th (T. Sreewongchai)

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male and female lines combining ability should be known to exploit maximum heterosis using the three-line hybrid rice system in a hybrid program. The parental performance may not certainly disclose not indicate good or bad combining ability. Thus, it is essential to collect data on the effects and expression of specific genes such as combining ability. It also clarifies the natural genes features that complicate the inheritance of characters. General combining ability (GCA) is ascribed to additive gene effects and additive × additive epistasis and is supposedly fixable. Contrariwise, specific combining ability (SCA) is ascribable to non-additive gene action that may be owing to epistasis or dominance or both and is non-fixable. Owing to the genetic variance of a non-additive gene, it is the primary reasoning for beginning a hybrid scheme (Cockerham, 1961; Pradhan et al., 2006). It is necessary to study the numerous morphological characteristics to better appraise inheritance values and to choose or classify the excellent genotypes. The evaluation of heterosis is comprised of both additive and a higher amount of dominance or epistasis interactions or both for one or more morphological characters. Vanaja and Babu (2004) considered that the increasing rice yield was due to heterosis in the number of total spikelets per panicle, the area of the flag leaf and number of filled grains per panicle. The current study was conducted to evaluate the combining ability of 24 parental lines using 4 A-lines and 20 R-lines from different cooking quality groups to select superior genotypes.

Materials and Methods

Plant materials

The A-line and R-line were derived from the Hybrid Rice Breeding for High Yield and Quality for Industrial Processing Project Phase 1, during 2013–2015 by the Department of Agronomy, Faculty of Agriculture, Kasetsart University, Bangkok, Thailand. There were two different cooking quality groups in the A-line, with the first being KUA2 (SPR1^{A}) and KUA8 (RD43^{A}) with high amylose content and the second being KUA3 (HCS^{A}) and KUA7 (PTT1^{A}) with low amylose content and aroma. Twenty R-lines were divided into two groups: 1) the high amylose content group consisting of KUR1-18, KUR1-31, KUR3-79, KUR3-102, KUR4-120, KUR4-137, KUR7-197, KUR7-238, KUR9-271 and KUR9-288; and 2) the low amylose content and aroma group consisting of KUR2-51, KUR2-52, KUR2-54, KUR2-64, KUR8-7-10, KUR8-11-8, KUR8-14-2, KUR11-40, KUR11-188 and KUR11-286. RD49 and RDH1 were used as check varieties.

A factorial cross mating design was used in the crossings of A-lines and R-lines (Table 1) in January 2016 at the Rice Science Laboratory, Department of Agronomy, Kasetsart University. Consequently, there were 40 F_1 hybrids belonging to the high amylose content group and 20 crosses from using 2 female parents and 10 male parents and the absolute low amylose content and aroma group, where the 2 female parents were crossed with 10 male parents.

Experimental field

The test cross progenies and yield trial were conducted by in a randomized complete block design with spacing of 20 cm × 20 cm, from September 2016 to January 2017 in Bangsai, Phra Nakhon Si Ayutthaya, Thailand. The quantity of fertilizer ($N:P_2O_5:K_2O$ = 16:16:16) applied in the field was 312.5 kg/ha The protection of plant material involved using commercial pesticides. From each cross, three sample plants were selected to evaluate for days to 50% flowering (DTF), plant height (PH), number of tillers per plant (T/P), length of flagleaf (FLL), number of panicles per plant (P/P), length of panicle (PL), number of total grains per panicle (S/P), number of filled grains per panicle (G/P), 100-grain weight (GW) and yield per plant (Y).

Table 1 Cross combinations of A-line and R-line with different cooking quality groups of rice

No.	Cross from low amylose content and aroma group	No.	Cross from high amylose content group
1	KUA3/KUR2-51	21	KUA2/KUR1-18
2	KUA3/KUR2-52	22	KUA2/KUR1-31
3	KUA3/KUR2-54	23	KUA2/KUR3-79
4	KUA3/KUR2-64	24	KUA2/KUR3-102
5	KUA3/KUR8-7-10	25	KUA2/KUR4-120
6	KUA3/KUR8-11-8	26	KUA2/KUR4-137
7	KUA3/KUR8-14-2	27	KUA2/KUR7-197
8	KUA3/KUR11-40	28	KUA2/KUR7-238
9	KUA3/KUR11-188	29	KUA2/KUR9-271
10	KUA3/KUR11-286	30	KUA2/KUR9-288
11	KUA7/KUR2-51	31	KUA8/KUR1-18
12	KUA7/KUR2-52	32	KUA8/KUR1-31
13	KUA7/KUR2-54	33	KUA8/KUR3-79
14	KUA7/KUR2-64	34	KUA8/KUR3-102
15	KUA7/KUR8-7-10	35	KUA8/KUR4-120
16	KUA7/KUR8-11-8	36	KUA8/KUR4-137
17	KUA7/KUR8-14-2	37	KUA8/KUR7-197
18	KUA7/KUR11-40	38	KUA8/KUR7-238
19	KUA7/KUR11-188	39	KUA8/KUR9-271
20	KUA7/KUR11-286	40	KUA8/KUR9-288

Calculation of heterosis

Heterosis of yield was calculated as mid-parent heterosis (H_{MP}) = (F_1-MP)/MP×100, heterobeltiosis (H_{BP}) = (F_1-BP)/BP×100 and standard heterosis (H_{CK}) = (F_1-CK)/CK×100; where, F_1, BP and CK refer to the yield of F_1 hybrid, the better performing parent and the standard check, respectively, and MP = (P1+P2)/2 where P1 and P2 are the yields of the parents.

Statistical analysis

Analysis of general combining ability and specific combining ability

The data of agronomic traits, yield components and yield were analyzed using analysis of variance and means were compared using least significant differences (LSD) in the Crop Stat 7.2 package, with significance being tested as significant at $p < 0.05$ and highly significant at $p < 0.01$. The Genresearch program was used to calculate the GCA of each parent and the SCA of each parental pair.

Results

Factors affecting yield per plant

The analysis of variance results revealed significant effects for varieties, crosses, parents, parents versus crosses, and males and females on yield per plant. In the high amylose group, the results showed that the variety and male and female were highly significant, with crosses and parents versus crosses being significant, while parents were not significant, as shown in Table 2. On the other hand, the variety and parents were significant factors and the others were not significant in the low amylose group (Table 3).

Performance of hybrids rice lines

The evaluation of performance in the field revealed that differences among the high amylose group and the low amylose with aroma group of the traits as presented in Table 4 and Table 5, respectively. DTF in the low amylose with aroma group ranged from 87.24 to 95.41 with a mean of 88.93 d; in the high amylose content group DTF ranged from 87.24 to 94.95 with a mean of 89.42 d. Accordingly, DTF values for the 40 hybrids were similar to their parental lines (not shown). Plant height in the low amylose with aroma group ranged from 60.01 to 80.67 cm and the cross between KUA3 and KUR2-52 was the highest, in the high amylose content group, ranging from 71.65 to 97.32 cm, with the cross between KUA8 and KUR7-238 being the highest. FLL in the low amylose with aroma group ranged from 29.33 to 41.67 cm and the longest was for the cross between KUA3 and KUR2-51; in the high amylose content group FLL ranged from 20.67 to 39.00 cm and the cross between KUA8 and KUR1-31 was the longest. PL in the low amylose with aroma group ranged from 21.41 to 33.41 cm and the cross between KUA3 and KUR11-188 was the longest; in the high amylose content group PL ranged from 25.67 to 45.00 cm and the cross between KUA8 and KUR4-137 was the longest. T/P in the low amylose with aroma group ranged from 3.53 to 11.31 tillers and the cross between KUA3 and KUR8-11-8 had the highest value; in the high amylose content group, T/P ranged from 3.45 to 9.04 tillers and was highest for the cross between KUA2 and KUR1-31. P/P in the low amylose with aroma group ranged from 3.20 to 10.92 panicles and the cross between KUA3 and KUR8-11-8 had the highest value; in the high amylose content group, P/P ranged from 2.95 to 9.26 panicles, with the highest value being for the cross between KUA2 and KUR1-31. S/P in the low amylose with aroma group ranged from 105.80 to 246.40 grains and the cross between KUA7 and KUR2-64 had the highest value; in the high amylose content group, S/P ranged from 106.70 to 237.10 grains and the highest value was for the cross between KUA2 and KUR4-120. S/P in the low amylose with aroma group ranged from 79.51 to 168.20 grains and the highest value was for the cross between KUA7 and KUR11-40; in the high amylose content group, S/P ranged from 61.51 to 182.60 grains and the cross between KUA2 and KUR1-18 had the highest value. GW in the low amylose with aroma group ranged from 1.20 to 3.12 g and the highest value was for the cross between KUA7 and KUR2-51; in the high amylose content group, GW ranged from 2.59 to 3.45 g and the highest value was for the cross between KUA8 and KUR4-137. Y in the low amylose with aroma group ranged from 4.20 to 29.16 g and the cross between KUA3 and KUR8-11-8 had the highest value; in the high amylose content group, Y ranged from 1.76 to 23.68 g and the cross between KUA2 and KUR7-238 had the highest value.

Combining ability analysis

The results of the combining ability test showed significant differences among the yields of genotypes (Table 2 and Table 3). The genetic effects among the genotypes were partitioned into GCA and SCA. There are two directions in a trait concerned with the significance of GCA, so the parents can carry low or high values for a character that we can declare. Therefore, in cases where positive and negative values of a trait are wanted, the increasing and decreasing values of GCA should be considered.

Table 2 Analysis of variance of yield in high amylose group

Source	df	SS	MS	F
Varieties	31	2227.77	71.86	2.36^{**}
Crosses	19	1436.34	75.59	2.48^{*}
Parents	11	632.76	57.52	1.89^{ns}
Parents versus Crosses	1	158.66	158.66	5.21^{*}
Male	9	1141.55	126.84	11.26^{**}
Female	1	193.42	193.42	17.17^{**}
Error	31	944.72	30.47	1.00

*, ** and ns indicate significant at $p < 0.05$, $p < 0.01$ and not significant differences, respectively.

Table 3 Results of analysis of variance of rice yield in low amylose and aroma group

Source	df	SS	MS	F
Varieties	31	1988.16	64.13	1.99*
Crosses	19	1114.47	58.66	1.83ns
Parents	11	818.24	74.38	2.32*
Parents versus Crosses	1	55.45	55.45	1.73ns
Male	9	538.68	59.85	1.01ns
Female	1	44.27	44.27	0.75ns
Error	31	995.32	32.11	1.00

Note: *, ** and ns indicate significant at $p < 0.05$, $p < 0.01$ and not significant differences, respectively.

Table 4 Mean values of important agronomic traits of developed hybrid rice lines

No.	Cross	Block	DTF[z]	PH	FLL	PL	T/P
1	KUA3/KUR2-51	2	88.41	79.34	41.67	26.74	4.87
2	KUA3/KUR2-52	2	88.41	80.67	36.00	29.41	8.20
3	KUA3/KUR2-54	1	88.41	71.62	30.72	26.74	5.65
4	KUA3/KUR2-64	2	88.41	80.01	41.33	24.74	3.53
5	KUA3/ KUR8-7-10	1	88.41	72.62	30.39	25.07	5.31
6	KUA3/ KUR8-11-8	1	88.41	76.28	38.39	30.41	11.31
7	KUA3/ KUR8-14-2	1	88.41	71.28	38.06	29.41	7.31
8	KUA3/KUR11-40	1	88.41	65.95	35.06	25.41	5.65
9	KUA3/KUR11-188	1	88.41	75.28	40.39	33.41	6.31
10	KUA3/KUR11-286	1	88.41	71.95	35.72	21.41	4.98
11	KUA7/KUR2-51	3	87.24	72.06	32.94	29.19	8.37
12	KUA7/KUR2-52	3	87.24	77.39	34.28	32.85	8.37
13	KUA7/KUR2-54	2	95.41	76.34	34.67	29.41	6.54
14	KUA7/KUR2-64	3	87.24	76.73	36.28	30.52	8.04
15	KUA7/ KUR8-7-10	2	88.41	77.67	36.67	32.07	8.54
16	KUA7/ KUR8-11-8	2	88.41	69.01	29.33	21.07	3.87
17	KUA7/ KUR8-14-2	2	95.41	76.34	33.33	30.07	8.20
18	KUA7/KUR11-40	2	88.41	78.01	40.67	22.07	5.20
19	KUA7/KUR11-188	2	88.41	72.67	36.33	25.07	7.20
20	KUA7/KUR11-286	2	88.41	60.01	34.67	25.74	6.54
21	KUA2/KUR1-18	3	87.24	90.06	33.94	29.85	8.04
22	KUA2/KUR1-31	3	87.24	87.39	33.28	31.52	9.04
23	KUA2/KUR3-79	3	87.24	84.39	36.28	27.85	6.37
24	KUA2/KUR3-102	3	94.24	89.73	35.61	28.85	7.70
25	KUA2/KUR4-120	3	87.24	92.73	35.28	31.85	8.04
26	KUA2/KUR4-137	3	87.24	89.73	35.94	29.19	8.37
27	KUA2/KUR7-197	3	87.24	85.39	33.61	27.52	8.04
28	KUA2/KUR7-238	3	87.24	93.73	31.94	32.52	8.37
29	KUA2/KUR9-271	4	94.95	88.98	33.00	30.00	6.12
30	KUA2/KUR9-288	4	87.95	82.32	20.67	26.00	3.45
31	KUA8/KUR1-18	4	87.95	71.65	30.67	32.00	6.45
32	KUA8/KUR1-31	4	87.95	82.32	39.00	30.67	6.78
33	KUA8/KUR3-79	4	94.95	82.65	29.33	26.33	6.45
34	KUA8/KUR3-102	4	94.95	80.32	30.67	27.67	5.45
35	KUA8/KUR4-120	4	87.95	75.65	30.33	26.00	8.78
36	KUA8/KUR4-137	4	87.95	79.65	29.33	45.00	5.12
37	KUA8/KUR7-197	4	87.95	69.98	28.00	25.67	7.45
38	KUA8/KUR7-238	4	94.95	97.32	26.67	26.67	5.78
39	KUA8/KUR9-271	4	87.95	78.65	32.67	27.00	7.12
40	KUA8/KUR9-288	4	87.95	80.32	30.33	28.33	5.78
	LSD 0.05(1)		8.86	14.68	9.86	7.53	2.93
	LSD 0.05(2)		9.57	15.85	10.65	8.13	3.16

DTFz = days up to 50% flowering; PH = plant height (cm); FLL = flag leaf length (cm);
PL = panicle length (cm); T/P = number of tillers per plant; LSD 0.05(1) = two adjusted means in same block; LSD 0.05(2) = two adjusted means in different blocks.

Table 5 Mean values of important yield and yield components of developed hybrid rice lines

No.	Cross	Block	P/P[z]	S/P	G/P	GW	Y
1	KUA3/KUR2-51	2	4.20	189.10	146.20	1.62	11.56
2	KUA3/KUR2-52	2	7.54	208.40	136.50	1.52	16.48
3	KUA3/KUR2-54	1	5.26	144.80	115.10	2.99	13.20
4	KUA3/KUR2-64	2	3.54	223.80	166.80	1.51	10.62
5	KUA3/ KUR8-7-10	1	4.92	164.10	136.40	3.08	14.86
6	KUA3/ KUR8-11-8	1	10.92	181.40	147.10	3.06	29.16
7	KUA3/ KUR8-14-2	1	6.92	196.10	164.10	3.08	21.62
8	KUA3/KUR11-40	1	5.26	173.40	117.10	2.90	14.08
9	KUA3/KUR11-188	1	5.59	169.40	139.10	3.03	12.49
10	KUA3/KUR11-286	1	3.92	142.10	110.10	2.99	6.89
11	KUA7/KUR2-51	3	7.26	162.10	105.90	3.12	12.55
12	KUA7/KUR2-52	3	8.92	205.10	135.20	2.70	18.84
13	KUA7/KUR2-54	2	5.20	177.40	112.20	1.57	11.18
14	KUA7/KUR2-64	3	7.92	246.40	159.90	2.70	15.06
15	KUA7/ KUR8-7-10	2	7.20	207.80	134.80	1.50	16.89
16	KUA7/ KUR8-11-8	2	3.20	105.80	79.51	1.50	7.06
17	KUA7/ KUR8-14-2	2	7.54	203.10	142.80	1.28	15.11
18	KUA7/KUR11-40	2	5.20	245.80	168.20	1.20	15.68
19	KUA7/KUR11-188	2	6.54	138.40	107.80	1.55	13.35
20	KUA7/KUR11-286	2	5.20	162.80	97.18	1.38	4.20
21	KUA2/KUR1-18	3	8.59	220.80	182.60	3.07	22.40
22	KUA2/KUR1-31	3	9.26	198.40	165.90	2.90	23.55
23	KUA2/KUR3-79	3	6.59	176.40	146.20	3.12	16.76
24	KUA2/KUR3-102	3	7.26	216.10	168.90	2.97	18.40
25	KUA2/KUR4-120	3	7.59	237.10	181.90	2.78	20.27
26	KUA2/KUR4-137	3	7.92	231.40	133.60	2.59	18.00
27	KUA2/KUR7-197	3	8.59	174.80	141.90	2.90	18.17
28	KUA2/KUR7-238	3	8.92	224.40	171.90	2.94	23.68
29	KUA2/KUR9-271	4	5.95	229.70	180.80	2.96	16.77
30	KUA2/KUR9-288	4	2.95	129.70	100.20	3.13	4.23
31	KUA8/KUR1-18	4	6.28	159.00	119.80	2.97	18.54
32	KUA8/KUR1-31	4	6.62	180.00	140.80	3.01	20.59
33	KUA8/KUR3-79	4	6.28	163.00	118.50	3.22	11.77
34	KUA8/KUR3-102	4	5.28	117.00	71.18	3.23	9.13
35	KUA8/KUR4-120	4	8.62	106.70	80.18	3.28	13.07
36	KUA8/KUR4-137	4	4.95	201.40	111.20	3.45	10.52
37	KUA8/KUR7-197	4	5.62	108.00	90.85	2.98	12.19
38	KUA8/KUR7-238	4	5.62	224.00	181.50	2.92	21.49
39	KUA8/KUR9-271	4	6.95	185.00	136.20	3.06	19.19
40	KUA8/KUR9-288	4	4.95	145.40	61.51	3.23	1.76
	LSD 0.05(1)		3.25	66.60	54.75	5.04	9.40
	LSD 0.05(2)		3.51	71.94	59.41	5.44	10.15

P/Pz = number of panicles per plant; S/P = number of grains per panicle;
G/P = number of filled grain per panicle; GW = 100-grain weight (g); Y= yield per plant;
LSD 0.05(1) = two adjusted means in same block; LSD 0.05(2) = two adjusted means in different blocks.

Female parents (KUA3 as a representative of the low amylose with aroma group and KUA2 from the high amylose group) were good general combiners and had increased GCA effects for yield of 1.05 and 2.2, respectively (Table 6). Watanesk (1993) and Singh et al., (1996) described good cytoplasmic male sterile (CMS) parents related to yield and their contribution to traits in rice. The pollinators (KUR8-14-2, representative of the low amylose with aroma group and KUR7-238 from the high amylose group) were the best general combiners with high GCA effects for yield of 4.32 and 6.56, respectively.

The cross between KUA3 and KUR8-11-8 as candidate parents from the low amylose with aroma group and between KUA8 and KUR9-271, as representative of the high amylose group were the best specific cross combinations for the highest yield (Table 6). High effects of heterosis with good specific combing ability for yield and yield component characters were found in two cross combinations. Singh et al. (1996) and Rogbell et al. (1998) described good specific cross combiners in rice. Usually, at least one parent with low general combining ability was involved in many of the good specific combiners for a character in company with grain yield. This indicates both additive and non-additive types of gene action.

Table 6 General combining ability and specific combining ability values in yield per plant

F \ M	KUR1-18	KUR1-31	KUR3-79	KUR3-102	KUR4-120	KUR4-137	KUR7-197	KUR7-238	KUR9-271	KUR9-288	GCA
KUA2	-0.27	-0.72	0.30	2.44	1.40	1.54	0.79	-1.10	-3.41	-0.96	2.20
KUA8	0.27	0.72	-0.30	-2.44	-1.40	-1.54	-0.79	1.10	3.41	0.96	-2.20
GCA	4.45	6.05	-1.76	-2.26	0.65	-1.76	-0.84	6.56	1.96	-13.03	
F \ M	**KUR8-7-10**	**KUR8-11-8**	**KUR8-14-2**	**KUR2-51**	**KUR2-52**	**KUR2-54**	**KUR2-64**	**KUR11-40**	**KUR11-188**	**KUR11-286**	**GCA**
KUA3	-2.07	9.99	2.20	-1.55	-2.23	-0.04	-3.27	-1.85	-1.48	0.29	1.05
KUA7	2.07	-9.99	-2.20	1.55	2.23	0.04	3.27	1.85	1.48	-0.29	-1.05
GCA	1.83	4.07	4.32	-1.99	3.62	-1.85	-1.20	0.84	-1.12	-8.50	

Upper table shows high AC; SE of GCA for male and female = 2.83 and 1.26, respectively./SE of SCA for F_1 hybrids = 4.01
And lower table shows low AC, aroma; SE of GCA for male and female = 2.76 and 1.23, respectively./SE of SCA for F_1 hybrids = 3.90

Evaluation of heterosis

It is vital to classify the probable maintainer and restorer lines from the rice germplasm source for a hybrid rice breeding program. The evaluation data of heterosis and heterobeltiosis showed that the heterosis in yield values were in the range 74.26–106.81% in the low amylose with aroma group and from -75.33% to 106.61% in the high amylose group and that of heterobeltiosis were from -78.48% to 54.2% in the low amylose with aroma group and from -80.2% to 92.58% in the high amylose group (Table 7). Five hybrids in the low amylose with aroma group had positive heterosis and heterobeltiosis, namely the crosses between KUA3 and KUR8-14-2 (H_{MP} = 80.85, H_{BP} = 14.33), between KUA3 and KUR8-11-8 (H_{MP} = 106.81, H_{BP} = 54.20), between KUA7 and KUR8-7-10 (H_{MP} = 38.78, H_{BP} = 28.74), between KUA7 and KUR8-14-2 (H_{MP} = 66.78, H_{BP} = 15.17) and between KUA7 and KUR11-188 (H_{MP} = 15.09, H_{BP} = 1.75), with the cross between KUA7 and KUR2-52 being the only one with positive heterosis of 2.20. Furthermore, the cross between KUA3 and KUR8-11-8 had the highest heterosis and heterobeltiosis values of 106.81%and 54.2%, respectively. Of the 16 hybrids, 9 in the high amylose group had positive heterosis and heterobeltiosis, namely the crosses between KUA2 and KUR1-31 (H_{MP} = 9.74, H_{BP} = 9.23), between KUA2 and KUR1-18 (H_{MP} = 33.89, H_{BP} = 4.87), between KUA2 and KUR7-238 (H_{MP} = 20.88, H_{BP} = 10.86), between KUA8 and KUR1-18 (H_{MP} = 101.19, H_{BP} = 53.22), between KUA8 and KUR3-102 (H_{MP} = 23.05, H_{BP} = 7.29), between KUA8 and KUR4-120 (H_{MP} = 42.14, H_{BP} = 8.37), between KUA8 and KUR7-238 (H_{MP} = 77.97, H_{BP} = 20.60), between KUA8 and KUR7-197 (H_{MP} = 106.61, H_{BP} = 92.58) and between KUA8 and KUR9-271 (H_{MP} = 104.26, H_{BP} = 54.01). However, there was only positive heterosis for the crosses between KUA2 and KUR3-102 (H_{MP} =23.20), between KUA2 and KUR4-120 (H_{MP} =21.31), between KUA2 and KUR4-137 (H_{MP} =1.18), between KUA2 and KUR7-197 (H_{MP} = 35.45), between KUA8 and KUR1-31 (H_{MP} = 47.65), between KUA8 and KUR3-79 (H_{MP} = 19.13) and between KUA8 and KUR4-137 (H_{MP} = 2.38). The standard heterosis value of yield in hybrids compared with the commercial variety RD49 was highest for the hybrid of KUA3 and KUR8-11-8 (170.25%) in the low amylose with aroma group, and for the hybrid of KUA2 and KUR7-238 (119.46%) in the high amylose group. The standard heterosis value compared with the commercial hybrid variety RDH1 displayed the same trend to the standard heterosis value of yield in hybrids for the commercial variety RD49 (Table 7).

Discussion

The gene action data of particular varieties and traits might be utilized depending on the breeding goals. Investigating the effects of GCA showed the presence of good general combining ability in grain yield and the other characters. Therefore, these males and females with general combining ability may be utilized in a future hybrid rice breeding program. The effect of SCA is the key to deciding the utility of a certain cross combination in the exploitation of heterosis.

The current study selected parental lines from hybrid rice based on evaluation days to 50% flowering, combining ability, yield and heterosis and similar findings have been reported by Jayasudha and Sharma (2002), Chansong (2010), Saidaiah et al., (2010) and Saengsawong (2012).

Synchronization in flowering among the parents in hybrid rice production is necessary to produce a higher seed yield. Parents differ in flowering due to their genetic characters and their differential responses to changes in environmental conditions (Biradarpatil and Shekhargouda, 2006; Mondo et al., 2016). Therefore, the current study selected parental lines that had similar days of flowering.

In the current study, the SCA effects were high and positive for yield in the cross combinations of KUA3 and KUR8-11-8 (as candidate parents from the low amylose with aroma group) and between KUA8 and KUR9-271 (as representative of the high amylose group). The results were similar to Rao et al. (1996). The investigation of combining ability aids in the identification of parents having high GCA and good combinations with high SCA effects (Jayasudha and Sharma, 2002). GCA designates the combining ability of the parents for a character, while SCA relates to a particular cross between two parents (Yang et al., 1997; Vacaro et al., 2002). Usually, GCA is considered to be controlled by additive gene action. If the parental lines have a high GCA value, it will be suitable for use as a tester in the evaluation of combining ability next time. SCA is considered to be controlled by non-additive gene action. Consequently, a high SCA value is best for applying to a commercial hybrid variety (Sumpantharak, 2008).

The percentages of mid-parent heterosis, better parent heterosis and standard heterosis were calculated for the yield and yield components characters. The yield-related traits of F_1 hybrids were typically utilized to discover methods for the assessment and prediction of heterosis in rice yield (Xangsayasane et al., 2010; Melchinger et al., 2008; Gartner

Table 7 Mean estimates for yield of hybrids on mid-parent heterosis, heterobeltiosis and standard heterosis

No.	Cross	Yield			
		Mid-parent heterosis	Heterobeltiosis	Standard heterosis	
				RD49	RDH1
1	KUA3/KUR2-51	-35.29	-38.87	7.13	-17.01
2	KUA3/KUR2-52	-22.74	-30.61	52.73	18.31
3	KUA3/KUR2-54	-33.11	-35.80	22.34	-5.24
4	KUA3/KUR2-64	-50.43	-55.63	-1.58	-23.76
5	KUA3/ KUR8-7-10	-1.36	-21.42	37.72	6.68
6	KUA3/ KUR8-11-8	106.81	54.20	170.25	109.33
7	KUA3/ KUR8-14-2	80.85	14.33	100.37	55.20
8	KUA3/KUR11-40	-26.49	-27.42	30.49	1.08
9	KUA3/KUR11-188	-13.83	-33.95	15.76	-10.34
10	KUA3/KUR11-286	-64.13	-64.68	-36.12	-50.52
11	KUA7/KUR2-51	-16.17	-25.39	16.31	-9.91
12	KUA7/KUR2-52	2.20	-20.67	74.61	35.25
13	KUA7/KUR2-54	-33.61	-45.62	3.61	-19.74
14	KUA7/KUR2-64	-18.73	-37.09	39.57	8.11
15	KUA7/ KUR8-7-10	38.78	28.74	56.53	21.25
16	KUA7/ KUR8-11-8	-36.99	-46.19	-34.56	-49.31
17	KUA7/ KUR8-14-2	66.78	15.17	40.04	8.47
18	KUA7/KUR11-40	-3.57	-19.18	45.32	12.56
19	KUA7/KUR11-188	15.09	1.75	23.73	-4.16
20	KUA7/KUR11-286	-74.26	-78.47	-61.04	-69.82
21	KUA2/KUR1-18	33.89	4.87	107.60	60.80
22	KUA2/KUR1-31	9.74	9.23	118.26	69.06
23	KUA2/KUR3-79	-3.65	-21.54	55.33	20.32
24	KUA2/KUR3-102	23.20	-13.86	70.53	32.09
25	KUA2/KUR4-120	21.31	-5.10	87.86	45.51
26	KUA2/KUR4-137	1.18	-15.73	66.82	29.22
27	KUA2/KUR7-197	35.45	-14.93	68.40	30.44
28	KUA2/KUR7-238	20.88	10.86	119.46	69.99
29	KUA2/KUR9-271	-0.83	-21.49	55.42	20.39
30	KUA2/KUR9-288	-71.13	-80.20	-60.83	-69.66
31	KUA8/KUR1-18	101.19	53.22	71.83	33.09
32	KUA8/KUR1-31	47.65	-4.50	90.82	47.81
33	KUA8/KUR3-79	19.13	-12.36	9.08	-15.51
34	KUA8/KUR3-102	23.05	7.29	-15.36	-34.44
35	KUA8/KUR4-120	42.14	8.37	21.13	-6.17
36	KUA8/KUR4-137	2.38	-26.02	-2.50	-24.48
37	KUA8/KUR7-197	106.61	92.58	12.97	-12.49
38	KUA8/KUR7-238	77.97	20.60	99.17	54.27
39	KUA8/KUR9-271	104.26	54.01	77.85	37.76
40	KUA8/KUR9-288	-75.33	-77.83	-83.66	-87.34

et al., 2009; Cho et al., 2004). Heterosis for yield is an important consideration in hybrid rice breeding. Yuan (2003) reported that H_{MP} may not be enough to use for commercial hybrid varieties—there must be H_{CK}. Therefore, the current study compared H_{MP}, H_{BP} and H_{CK}. The cross between KUA3 and KUR8-11-8 had the highest H_{MP}, highest H_{BP} and highest H_{CK} because yield is controlled by dominance effects, similar to the conclusions reported by Xiao et al., (1995) and Tokatlidis et al., (1998). Cross combination with an H_{CK} value of more than 20%, can be used for a commercial hybrid variety (Virmani et al., 1997). Hybrids with positive and significant SCA effects and values of H_{MP}, H_{BP} and H_{CK} will be needed for further testing in observational or multi-locational yield trials or both to explore the fertilization rate and probable heterosis.

Female lines (KUA3 from the low amylose with aroma group and KUA2 from the high amylose group) had high GCA values. In the male lines, KUR8-11-2 from the low amylose and aroma group and KUR7-238 from the high amylose group had high GCA. The highest SCA was found for the cross combinations between KUA3 and KUR8-11-8 in the low amylose and aroma group and between KUA8 and KUR9-271 in the high amylose group. The crosses between KUA3 and KUR8-11-8 had high H_{CK} values of 170.25% and 109.33% compared to the commercial varieties RD49 and RDH1, respectively. Thus, these two combinations can be used as parents for future commercial hybrid rice production.

Conflict of Interest

The authors assert that there are no conflicts of interest.

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