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Research Article

Heterosis and inbreeding depression in Aus Rice (*Oryza sativa* L.) for yield contributing traits

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Abstract

The extent of relative heterosis (RH) and heterobeltosis (HB) of 17 F_1s and inbreeding depression (ID) in 15 F_2 generations of Aus rice were estimated for 13 yield traits. The F_1s revealed significant negative heterosis for days to panicle exertion, days to maturity, plant height, empty grains/panicle, grain breadth in $P_1 \times P_4$, $P_2 \times P_1$, $P_2 \times P_5$, $P_3 \times P_4$, $P_6 \times P_4$, $P_6 \times P_{11}$ and $P_7 \times P_{11}$ which indicated the possibility of superior segregants for desirable types. Significant and positive heterosis was found in the crosses $P_1 \times P_4$, $P_2 \times P_1$, $P_2 \times P_6$, $P_3 \times P_4$, $P_4 \times P_6$ for effective tillers/plant, filled grains/panicle, 1000-seed weight and grain yield/plant. Heterosis for filled grains/panicle was significant positive in ($P_3 \times P_4$) over mid parent and better parent. The highest significant positive RH and BH was exhibited by crosses $P_8 \times P_3$ (34.08 and 18.65), $P_2 \times P_6$ (23.58 and 8.53), $P_6 \times P_3$ (16.97 and 15.27), $P_3 \times P_4$ (11.66 and 11.10) for panicle length. Significant positive RH was observed in F_1s $P_3 \times P_4$ (160.22) and $P_4 \times P_6$ (63.68), and $P_3 \times P_4$ (88.85) showed desirable HB for grain yield/plant. High degree of ID was manifested by tillers/plant, empty grains/panicle, panicle length, grain breadth and 1000-seed weight in F_1s P_6 x P_7, P_1 x P_4, P_7 x P_6, P_1 x P_4 and P_6 x P_7, respectively. Tillers/plant manifested positive and high ID in F_2 of P_6 x P_7 (42.56). The F_2 of P_7 x P_6 (-15.1) had the highest negative ID for panicle length. All crosses showed significant ID for filled grains/panicle except P3 x P4 and P6 x P7. The F_2 populations of P_6 x P_7 (14.55) showed the highest positive ID for 1000-grain weight. The highest negative ID was observed in F_2 generation of the cross $P_1 \times P_4$ (-158.74) for seed yield per plant and the highest positive value in the F_2 generation of $P_3 \times P_4$ (44.84). It can be concluded that hybrid breeding would be more effective for effective tillers/plant, filled grains/panicle, 1000-seed weight and grain yield/plant in rice as they exhibited relative heterosis and heterobeltiosis in desired (positive) direction. On the other hand, plant height and days to maturity revealed negative association grain yield per plant as they exhibited negative estimates of relative heterosis and heterobeltiosis.

Keywords: Aus rice, recombination, heterosis, segregation, grain yield.

INTRODUCTION

Rice is the most important cereal crops grown in Aus (April/April-June/July), Aman (July/August-November/December) and Boro (December/January-April) seasons in Bangladesh and some parts of India (Mamun *et al.,* 2021). Though rice is an annual plant, it can survive as a perennial in the tropics, and can produce a ratoon crop for up to three decades (www.en.wikipedia.org/wiki/Rice). It is the staple food of Bangladesh as well as other Asian countries. It is grown on 75% of the total cultivated land, constituting 90% of the total food grain production in Bangladesh (BBS, 2022). It is also staple food for Asian countries and per capita consumption of rice varies around 114 kg per year (Amirtham and Radha, 2023). Bangladesh was the third-largest rice producer in the world and the average rice production during 2023 was 39.1 million tonnes, but its productivity was low compared to other Asian countries, such as China, India, Thailand and Indonesia (FAOSTAT, 2024).

Rice production must be increased to keep pace with population growth. The production potential of rice in summer (Aus) and rainy (Aman) seasons remains adequately unexplored. Most of the rice grown in Aus season is long duration and low yielding (Bhattacharya *et al.,* 2019). More than 1000 Aus rice land races were cultivated traditionally and maintained for a long time by the farmers of Bangladesh for their high adaptability (Shelley *et al.,* 2016). These local cultivars of Aus rice can be used in breeding program to develop high yielding, short duration varieties with wider adaptability. It could open a new era to increase rice production in Aus season through the development of new short-duration and high-yielding rice varieties (Kahani and Hittalmani, 2015).

There are several methods to improve crop varieties, such as hybrid breeding, ideotype breeding, enhancement of photosynthesis, exploitation of wild species, genomic approaches and physiological approaches (Khush, 2013). Among the different options available to increase yield, hybrid breeding is the most feasible option (Yuan, 2009). The magnitude of heterosis helps in the identification of potential cross combinations to be used in conventional breeding to create wide array of variability in the segregating generations (Belaj *et al.,* 2002). The crosses between the different genotypes with maximum genetic divergence would be responsible for improvements as they yield desirable recombinants in the progeny (Kahani and Hittalmani, 2015). Segregating populations are more important for improving plant types by adopting selection (Savitha and Kumari, 2015). The present study was aimed to quantify the extent of heterosis in F_1 and inbreeding depression in F_2 generation for yield and related traits of Aus rice.

MATERIALS AND METHODS

The experiment was conducted at the field laboratory of the Department of Genetics and Plant Breeding, Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU), Gazipur during Aus season of 2018 and 2019. The F_1 generations were developed by crossing among the selected parents (**Table 1**) and F_2 generations were developed by inbreeding of F_1s. The experimental materials comprised of 17 F_1 and 15 F_2 families and their respective parents of Aus rice.

Pre-germinated seeds of the experimental materials were sown in well prepared nursery bed for quick germination and seedling production. Twenty-five days old seedlings were transplanted in the field with a spacing of 20 cm × 20 cm following Randomized Complete Block Design (RCBD) with three replications. Each replication had 25 individual plants from each genotype. Manure and fertilizers were applied as per BRRI recommendation (BRRI, 2018). Data were recorded on days to panicle exertion (DPE), plant height (PHT), days to maturity (DMT), number of tillers per plant (TPP), number of effective tillers per plant (ETP), number of non-effective tillers per plant (NET), number of filled grains (FGP), number of empty grains (EGP), panicle length (PLT), length of grain (GLT), breadth of grain (GBD), plant residue weight (PRW), 1000-seeds weight (TSW), grain yield per plant (YPP).

Statistical analyses

Analysis of variance was carried out separately for parental, F_1 and F_2 generations. Mean, standard error (SE), coefficient of variation (CV) were calculated from the replicated data of different characters by using computer software 'STAR' (Statistical Tools for Agricultural Research) according to Panse and Sukhatme (1957). Heterosis was expressed as percent increase or decrease in the mean value of F_1 over the mid parent (relative heterosis) and better parent (heterobeltiosis), on the other hand, inbreeding depression as percent increase or decrease in the mean value of F_1 over F_2 (Singh and Chaudhary, 1985).

Inbreeding depression is estimated using F_1 and F_2 population according to Talebi *et al*. (2010).

$$\text{Inbreeding depression} = \{(F_1 - F_2)/\ F_1\} \times 100$$

Where,

F_1 and F_2 are the mean value of F_1 and F_2 progeny.

Table 1. List of cross combinations used in the experiment

Crosses	Designations	Crosses	Designations
$P_1 \times P_4$	Dhalasaitta × N-ABSS	$P_6 \times P_3$	BRRI dhan55 × Kataktara
$P_2 \times P_1$	Laksmilota × Dhalasaitta	$P_7 \times P_3$	BR7 × Kataktara
$P_2 \times P_5$	Laksmilota × BRRI dhan43	$P_7 \times P_6$	BR7 × BRRI dhan55
$P_2 \times P_6$	Laksmilota × BRRI dhan55	$P_8 \times P_3$	Japonica rice × kataktara
$P_3 \times P_4$	Kataktara × N-ABSS	$P_6 \times P_4$	BRRI dhan55 × N-ABSS
$P_3 \times P_6$	Kataktara × BR55	$P_8 \times P_7$	Japonica rice × BR7
$P_3 \times P_7$	Kataktara × BR7	$P_6 \times P_{11}$	BRRI dhan55 × Parija
$P_4 \times P_6$	N-ABSS × BRRI dhan55	$P_7 \times P_{11}$	BR7 × Parija
$P_6 \times P_7$	BRRI dhan55 × BR7		

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RESULTS AND DISCUSSION

Heterosis expresses the superiority of the F_1 hybrid over its parents in terms of yield and other related traits. On the other hand, inbreeding depression ascertains the reduction or loss in vigor, fertility and yield as a result of inbreeding. The knowledge of heterosis along with the extent of inbreeding depression in subsequent generations is essential for maximum exploitation of such heterosis by adopting appropriate breeding methodology. The magnitude of heterosis helps in the identification of potential cross combinations to be used in conventional breeding program to enable a wide array of variability in segregating generations. The extent relative heterosis and heterobeltosis were estimated for 13 characters in 17 F_1 hybrid combinations and the same is furnished in **Tables 2 and 3**. The estimates of inbreeding depression for the 13 traits for 15 F_2 families were calculated and it is presented in **Table 4**.

The estimates of relative heterosis in 17 F_1s ranged from -15.32 (P_7 × P_{11}) to 33.21% (P_8 × P_3). Highly significant positive mid parent heterosis was recorded in P_8 × P_3 (33.21%) followed by P_6 × P_3 and P_3 × P_4 (**Table 2**). The $F_{1,}$ P_7 × P_{11} (15.32) showed highly significant negative mid parent heterosis for plant height, which is desirable since dwarfness is an important character in rice as it contributes to lodging resistance (Bhattarai *et al.,* 2021). The highest significant positive heterobeltosis was observed in the cross P_8 × P_3 (95.86) for plant height while the cross P_2 × P_1 (-18.3) revealed significant negative heterobeltosis and the cross P_7 × P_3 showed non-significant negative heterobeltosis (**Table 3**). The present findings are in accordance with the results reported by Parihar and Pathak (2008), Venkatesan *et al.* (2008), Tiwari *et al.* (2011), Kumar *et al.* (2012), and Sarkar *et al.* (2024). The F_2 progeny of the cross P_8 x P_3 (22.42) manifested positive inbreeding depression followed by P_6 x P_3 (16.26), P_2 x P_6 (15.31) and the F_2 progeny of the crosses P_2 x P_1 (-26.51), P_2 x P_5 (-5.64) showed negative inbreeding depression for plant height (**Table 4**). The inbreeding depression results due to fixation of unfavorable recessive genes in the individuals of F_2 and dominant genes in other individuals which causes decrease in vigor of the traits.

The cross P_8 × P_7 (8.81 and 15.75) exhibited the highest positive and significant relative heterosis (8.81) and heterobeltiosis (15.75) (**Table 2 and Table 3**). Significant and negative relative heterosis was observed in 11 crosses with the highest in P_2 × P_5 (-6.6) for days to maturity, which is desirable for this trait. Most of the F_1 hybrids flowered earlier than their mid-parents showing negative heterosis. Similar result was also reported by Murayama and Sarker (2002). The crosses P_2 × P_5 (-5.96), P_1 × P_4 (-4.63), P_6 × P_4 (-4.51), P_3 × P_4 (-3.72) and P_6 × P_{11} (-3.11) showed significant negative heterobeltosis for days to maturity. The results indicated that these hybrids possess genes for earliness. The F_2 populations of P_2 x P_5 (-8.44) exhibited non-significant negative inbreeding depression followed by P_6 x P_4 (-5.84), P_3 x P_4 (-3.95) and the F_2 populations of P_7 x P_6 (10.9) showed non-significant positive inbreeding depression for days to maturity followed by P_6 x P_7 (9.82), P_3 x P_7 (7. 28) (**Table 4**). The exhibited non-significant inbreeding depression indicated the chance of transgressive segregation for this trait.

Significant and negative heterosis was observed in the crosses P_2 × P_5 (-65.7), P_6 × P_{11} (-53.16), P_6 × P_4 (-26.79). Significant and negative heterobeltosis was observed in the crosses P_2 × P_5 (-752), P_6 × P_{11} (-62.5), P_7 × P_{11} (-37.5), P_6 × P_3 (-36.4) and P_3 × P_6 (-36.4) for number of tillers per plant. The extent of heterosis for number of tillers per plant was observed to be low and mostly in negative direction when compared to parental values. Significant positive average heterosis and heterobeltiosis was observed for tillers per plant (Devi *et al.*, 2018). This trait also manifested positive and high inbreeding depression in the F_2 populations of P_6 x P_7 (42.56) followed by P_8 x P_3 (36.38) and P_4 x P_6 (34.9). The results indicated that degree of inbreeding depression observed in F_2s is related to the magnitude of heterosis observed in F_1s .

The crosses P_2 × P_1 (111.11), P_1 × P_4 (96.52), P_2 × P_6 (78.37), P_4 × P_6 (38.03) showed significant and positive mid parent heterosis for number of effective tillers per plant (**Table 2**). None of the cross showed significant positive values for heterobeltosis (**Table 3**). Significant positive heterosis for number of effective tillers per plant was earlier observed by Singh *et al.* (1980), Anandakumar and Sree Rangasamy (1986). Khan *et al.* (1998) also reported positive heterosis for number of panicles per plant in F_1 hybrids of rice. Basavaraja *et al.* (1998) also reported that number of productive tillers per plant can have a high positive effect towards grain yield per plant. Significant positive average heterosis and heterobeltiosis was also observed for effective tillers per plant in rice by Devi *et al.* (2018). Number of effective tillers per plant showed non-significant positive inbreeding depression for the F_2 populations of P_6 x P_7 (45.14). Non-significant negative inbreeding depression was observed for number of effective tillers per plant in the F_2 populations of P_3 x P_6 (-10.38). Positive inbreeding depression was observed in the F_2 populations of P_8 x P_3 (95.06) followed by P_1 x P_4 (62.48) and P_4 x P_6 (53.5) for this trait, while negative inbreeding depression was observed in the cross P_6 x P_3 (-645.45).

The cross P_3 × P_4 (93.95 and 47.19) exhibited the highest positive and significant relative heterosis and heterobeltiosis for number of filled grains per panicle which is desirable (**Table 2**). Eleven crosses exhibited significant negative heterobeltiosis for number of filled grains per panicle (**Table 3**), among them the cross P_6 × P_{11} (-67.51) exhibited the highest negative value. All the F_2 families showed non-significant negative inbreeding depression except P_3 x P_4 (32.56) and P_6 x P_7 (16.4)

Table 2. Estimation of mid-parent heterosis for 13 agronomic traits in 17 Aus rice hybrids

Genotypes	DPE	PHT	DMT	TPP	ETP	NET	FGP	EGP	PLT	GLT	GBD	TSW	YPP
P1 × P4	6.19	-4.02	-4.67**	36.84	96.52**	-25.47	-4.95	140.42**	8.92*	13.92	-19.90**	0.02	0.05
P2 × P1	7.95	-8.33**	-1.86 **	-7.99	111.11*	-73.9**	-15.04	74.29	7.20	-3.93	-12.44**	-5.89	81.62
P2 × P5	2.99	3.85**	-6.6**	-63.57**	-42.85*	-85.47**	-25.96	-53.00**	3.40	-11.11	3.50	14.29*	-48.33
P2 × P6	9.89	23.28	-1.87**	26.31	78.37**	-19.21	-26.54*	139.08**	23.58**	-0.02	-4.59	4.59	32.66
P3 × P4	-11.73**	15.17**	-3.74**	-12.40	1.83	-50.58*	93.95**	-5.12	11.66**	13.16	6.28	36.12**	160.22**
P3 × P6	-5.85	-13.12**	-1.87**	-24.61	4.69	-75.84**	-15.72*	19.94	3.67	-2.35	-8.94*	-13.02	-18.34
P3 × P7	3.25	4.50	1.76**	-8.85	9.17	-58.1	-34.37**	48.61**	7.69*	-2.81	-5.34	4.43	-26.75*
P4 × P6	-5.79*	2.48	-2.81**	-13.72	38.03*	-81.54**	8.79	-22.28*	-3.35	2.54	1.01	16.08*	63.68*
P6 × P7	4.28	7.97	3.53**	-14.59	11.11	-69.99*	-18.61*	-21.48*	-2.54	4.52	-12.37**	-0.32	-9.85
P6 × P3	1.95	26.96**	1.87**	-24.62	12.17	-95.22**	-1.26	23.53	16.97**	5.42	5.26	14.16	28.78
P7 × P3	3.25	-3.41	2.64**	4.40	15.27	-25.41	-27.00**	16.23	9.85**	-0.56	4.81	5.39	-12.73
P7 × P6	4.28	-10.29**	5.29**	-12.90	9.33	-48.38	-14.49	2.30	-9.45**	-6.97	-8.24*	-12.11	-18.56
P8 × P3	-6.89*	33.21**	-2.01**	-14.06	-19.19	-10.42	17.45	-5.32	34.08**	6.84	-5.18	11.76	25.52
P6 × P4	-6.95*	-2.64	-4.69**	-26.79*	28.63	-84.58**	-10.96	2.32	-1.63	2.09	0.50	9.79	22.82
P8 × P7	4.32	0	8.81**	0	0	0	0	0	0	0	0	0	0
P6 × P11	-8.48	-3.83	-3.78**	-53.16**	-53.00**	-48.58	-62.95**	48.55**	3.78	1.30	-18.64**	0.02	0
P7 × P11	-3.35	-15.32**	-2.66**	-14.89	-20.45*	46.64	-34.21**	-25.23	-6.79*	-6.69	-24.20**	-1.15	-44.75**

*, ** represent significant at 5% and 1% level, respectively;

DPE- Days to panicle exertion, PHT- Plant height, DMT- Days to maturity, TPP- Tillers per plant, ETP- Effective tillers per plant, NET- Non effective tiller per plant, FGP- Filled grain, EGP- Empty grain, PLT- Panicle length, GLT- Length of grain, GBD- Breadth of grain, TSW- 1000-Seeds weight, YPP- Yield per plant.

Table 3. Estimation of heterobeltosis for 13 agronomic traits of 17 F_1 Aus rice hybids

Genotypes	DPE	PHT	DMT	TPP	ETP	NET	FGP	EGP	PLT	GLT	GBD	TSW	YPP
P1 × P4	13.84**	7.42	-4.63**	2.63	33.33	-8.33	-10.52	317.23**	3.08	10.53	-12.3**	-19.39*	-24.51
P2 × P1	8.19*	-18.3**	-1.77**	-9.21	90	-72.7*	-22.25	184.66*	-0.08	-4.11	-8.47*	-12.46*	61.27
P2 × P5	6.51*	11.16*	-5.96**	-75.2**	-65.9**	-79.5**	-36.63*	88.24	-7.18	-18.4*	20.34**	-4.03	-68.67**
P2 × P6	17.77**	37.21**	-1.74**	-6.49	13.79	-4.54	-41.44**	765.41**	8.53*	-9.66	10.43*	-7.32	-19.48
P3 × P4	-10.86**	25.9**	-3.72**	-25.7	1.19	-9.26	47.19**	16.55	11.1**	10.29	10.95*	27.33*	88.85**
P3 × P6	-4.74	0.17	-1.66**	-36.4*	2.29	-56.5	-30.95**	57.39**	2.16	-11.5	-5.07**	-22.44**	-25.02
P3 × P7	13.15**	6.52	8.19**	-14.2	-0.98	-55	-34.39**	140.49**	2.41	-9.93	-2.79	-2.54	-37.02**
P4 × P6	-5.61	7.82	-2.63**	-14.3	35.63	-80	-1.48	-17.82	-4.29	-9.89	1.46	-2.37	26.06
P6 × P7	12.84**	10.6*	10.33**	-24	2.94	-40	-33.32**	-6.7	-6.01	2.01	-11.3*	-5.08	-27.8*
P6 × P3	3.16	46.08**	2.09**	-36.4*	9.56	-91.3	-19.09*	62.11**	15.27**	-4.47	9.35*	**1.83**	18.22
P7 × P3	13.15**	-1.55	9.13**	-1.68	4.54	-20	-27.03**	88.09**	4.46	-7.77	7.23	-1.64	-24.97*
P7 × P6	12.84**	5.7	12.21**	-22.5	1.29	3.3	-29.96**	21.57	-12.67**	-9.18	-7.16*	-16.33*	-34.78*
P8 × P3	-6.61*	95.86**	-1.96**	-8.33	-27.6	47.82	-31.27**	13.34	18.65**	3.01	10.35*	-0.93	-20.45
P6 × P4	-6.77*	2.26	-4.51**	-27.3	26.43	-83.3**	-19.38	8.19	-2.58	-10.3	0.69	-7.66	-5.4
P8 × P7	13.95**	50.77**	15.75**	-10	-1.42	82.5	-41.49**	30.19*	-15.28*	-10.3	12.97**	-5.41	-40.38**
P6 × P11	-4.02	1.34	-3.11**	-62.5**	-68.2**	44.33	-67.51**	137.02**	1.73	-7.19	-2.56	-14.54	-31.18**
P7 × P11	10.05**	5.97	4.49**	-37.5**	-43.7**	54.37	-39.25	50.12	-11.82**	-12.6	-7.7	-11.84	-55.08**

*, ** represent significant at 5% and 1% level, respectively;

DPE- Days to panicle exertion, PHT- Plant height, DMT- Days to maturity, TPP- Tillers per plant, ETP- Effective tillers per plant, NET- Non effective tiller per plant, FGP- Filled grain, EGP- Empty grain, PLT- Panicle length, GLT- Length of grain, GBD- Breadth of grain, TSW- 1000-Seeds weight, YPP- Yield per plant.

for filled grains per panicle. The highest positive and significant relative heterosis and heterobeltiosis was observed for number of effective tillers per plant in the crosses P_1 × P_4 (140.42 and 317.23), P_2 × P_6 (139.08 and 765.41), P_3 × P_7 (48.61 and 140.49) and P_6 × P_{11} (48.55 and 137.02). The crosses P_2 × P_5 (-53.00), P_4 × P_6 (-22.28) and P_6 × P_7 (-21.48) depicted significant negative heterosis over mid parent for number of empty grains per panicle (**Table 2**).

Significant positive heterobeltosis was recorded in five crosses and none of them showed significant negative heterobeltosis for this trait (**Table 3**). The F_2 families of P_1 x P_4 (63) showed significant positive inbreeding depression for the character empty grains per panicle, while the F_2 families of P_3 x P_4 (-56.29) and P_2 x P_5 (-56.19) showed non-significant negative inbreeding depression (**Table 4**). The results indicated that the degree of inbreeding depression observed in F_2s is related to magnitude of heterosis observed in F_1s for empty grains per panicle.

The crosses P_8 × P_3 (34.08 and 18.65), P_2 × P_6 (23.58 and 8.53), P_6 × P_3 (16.97 and 15.27), P_3 × P_4 (11.66 and 11.10) exhibited the highest positive and significant relative heterosis and heterobeltiosis for panicle length (**Tables 2 and 3**). Apart from the above, three more crosses P_7 × P_3 (9.85), P_1 × P_4 (8.92), P_3 × P_7 (7.69) also exhibited significant positive heterosis over mid parent. Significant positive average heterosis and heterobeltiosis was also observed for panicle length by Devi *et al.* (2018).The cross P_7 × P_6 (-9.45) and P_7 × P_{11} (-6.79) exhibited significant negative mid-parent heterosis, while the crosses P_8 × P_7 (-15.28), P_7 × P_6 (-12.67), P_7 × P_{11} (-11.82) showed significant negative heterobeltosis for panicle length. Most of the crosses showed non-significant negative inbreeding depression for the character panicle length which indicated that there is a possibility of transgressive segregation for this trait. The F_2 populations of P_7 x P_6 (-15.1) had the highest value of inbreeding depression for panicle length. On the other hand, the F_2 families of the crosses P_8 x P_3 (9.49), P_2 x P_6 (6.92), P_1 x P_4 (3.28) and P_3 x P_7 (0.89) showed non-significant positive inbreeding depression.

None of the crosses showed significant positive average heterosis and heterobeltiosis for grain length (**Table 2 and Table 3**). The crosses P_1 × P_4 (13.92), P_3 × P_4 (13.16) and P_8 × P_3 (6.84) exhibited non-significant positive heterosis and the cross P_2 × P_5 (-11.11) showed the highest non-significant negative heterosis. The cross P_2 × P_5 (-18.40) showed significant negative heterobeltosis for grain length (**Table 3**) and non-significant positive heterobeltosis for P_1 × P_4 (10.53), P_3 × P_4 (10.29), P_8 × P_3 (3.01). The F_2 families of the crosses P_6 x P_7 (7.8), P_8 x P_3 (6.72), P_1 x P_4 (5.63) and P_2 x P_5 (3.71) showed non-significant positive inbreeding depression for grain length while the F_2 generations of P_3 x P_6 (-5.53), P_7 x P_6 (-2.59) and P_3 x P_4 (-1.14) showed non-significant negative value for inbreeding depression (**Table 4**). There was no hybrid combination having significant positive heterosis over mid parent and better parent for grain breadth. The crosses P_7 × P_{11} (-19.90), P_6 × P_{11} (-18.64), P_2 × P_1 (-12.44), P_6 × P_7 (-12.37), P_3 × P_6 (-8.94) and P_7 × P_6 (-8.24) showed significant negative heterosis over mid parent (**Table 2**). Six crosses showed significant positive heterobeltosis and five crosses *viz*., P_1 × P_4 (-12.3), P_6 × P_7 (-11.3), P_2 × P_1 (-8.47), P_7 × P_6 (-7.16) and P_3 × P_6 (-5.07) showed significant negative heterobeltosis for grain breadth (**Table 3**). Significant negative inbreeding depression was observed for grain breadth in the F_2 families of P_1 x P_4 (-62.62) followed by P_2 x P_1 (-59.26) and P_2 x P_5 (-56.27) (**Table 4**).

Thousand seed weight is one of the important traits which influence grain yield per plant (Singh and Patel, 2021). For 1000-seed weight, the cross P_3 × P_4 (36.12) showed significant positive heterosis followed by P_4 × P_6 (16.08) and P_2 × P_5 (14.29). The crosses P_6 × P_3 (14.16), P_8 × P_3 (11.76), P_6 × P_4 (9.79) manifested numerically higher positive heterosis over mid parent but the crosses P_3 × P_6 (-13.02), P_7 × P_6 (-12.11) and P_2 × P_1 (-5.89) showed non-significant negative heterosis over mid parent. The only cross P_3 × P_4 (27.33) manifested significant positive heterobeltosis and the cross P_3 × P_6 (-22.44) showed the highest significant negative heterobeltosis followed by P_1 × P_4 (-19.39), P_7 × P_6 (-16.33), P_2 × P_1 (-12.46). Ramakrishna *et al.* (2023) also reported significant heterosis for 1000-seed weight in rice. The F_2 families of crosses P_1 x P_4 (-17.91), P_2 x P_5 (-7.27), P_6 x P_4 (-5.96), P_7 x P_6 (-5.84), P_3 x P_6 (-1.77) showed non-significant negative inbreeding depression and P_6 x P_7 (14.55) showed the highest positive inbreeding depression for 1000- seed weight followed by the F_2 families of P_3 x P_7 (8.09) and P_6 x P_3 (7.61).

Out of the 17 F_1s, two crosses showed significant positive average heterosis and one cross showed significant better parent heterosis for grain yield per plant (**Table 2, Table 3**). The crosses P_3 × P_4 (160.22) and P_4 × P_6 (63.68) exhibited the highest significant positive relative heterosis and the cross P_3 × P_4 (88.85) showed desirable heterobeltiosis for grain yield per plant. Significant negative mid-parent heterosis was observed in the crosses P_7 × P_{11} (-44.75) and P_3 × P_7 (-26.75). The parent which had higher grain yield per plant is considered as better parent and heterobeltiosis is calculated by comparing F_1's with the performance of better parent (**Table 3**). Abdullah *et al.* (2018) also reported positive heterosis for grain yield per plant in F_1 hybrids of rice. The F_2 families of P_1 x P_4 (-158.74), P_2 x P_5 (-105.27), P_2 x P_1 (-52.41), P_3 x P_6 (-40.2), P_2 x P_6 (-13.69) and P_7 x P_6 (-8.18) exhibited non-significant negative inbreeding depression for grain yield per plant, which indicates chance of transgressive segregation for grain yield per plant in these families. On the other hand, the F_2 families of P_3 x P_4 (44.84), P_6 x P_3 (29.78), P_6 x P_7 (16.73), P_7 x P_{11} (15.44) showed non-significant positive inbreeding depression for grain yield per plant (**Table 4**). Heterosis for grain yield per plant

Table 4. Estimates of inbreeding depression for 13 agronomic traits of 15 F_2 population of Aus rice

Genotypes	DPE	PHT	DMT	TPP	ETP	NET	FGP	EGP	PLT	GLT	GBD	TSW	YPP
P1 × P4	13.92	12.29	-3.09	32.69	20.99	62.48	-72.51	63.00*	3.28	5.63	-62.62*	-17.91	-158.74
P2 × P1	18.02	-26.51	0.7	16.78	22.63	-4.50	-63.34	-6.99	-4.95	-0.97	-59.26*	1.86	-52.41
P2 × P5	9.31	-5.64	-8.44	10.94	16.71	14.00	-56.29	-56.19	-5.4	3.71	-56.27*	-7.27	-105.27
P2 × P6	14.7	15.31	-1.45	31.7	22.42	31.85	-93.16	57.17	6.92	0.52	-30.27	4.32	-13.69
P3 × P4	-18.26	7.42	-3.95	14.28	15.38	34.72	32.56	-56.29	-0.88	-1.14	-32.85	0.74	44.84
P3 × P6	9.95	4.4	-0.1	-22.65	-10.38	7.18	-37.67	35.41	-5.01	-5.53	-26.47	-1.77	-40.2
P3 × P7	-12.24	13.91	7.28	-8.21	12.41	-159.33	-34.17	26.81	0.89	0.48	-58.3	8.09	9.09
P4 × P6	6.15	5.6	-2.55	34.9	29.689	53.50	-63.52	14.59	-14.07	2.18	-19.9	3.46	7.63
P6 × P7	13.93	5.84	9.82	42.56	45.14	20.00	16.40	34.14	-5.78	7.8	-44	14.55	16.73
P6 × P3	-0.45	16.26	0.52	14.94	20.32	-645.45	-12.76	16.74	-2.12	3.57	-17	7.61	29.78
P7 × P3	5.97	8.14	-0.06	-8.79	9.73	-41.57	-30.44	19.9	-1.76	-6	-19.13	5.6	17.47
P7 × P6	13.1	2.38	10.9	7.14	5.86	34.59	-54.44	57.17	-15.1	-2.59	-28.76	-5.84	-8.18
P8 × P3	-2.43	22.42	-1.95	36.38	10.57	95.06	-37.12	21.31	9.49	6.72	-8.15	0.94	5.01
P6 × P4	0.82	6.85	-5.84	24.81	28.96	-14.37	-84.86	84.79	-6.93	3.59	-24.17	-5.96	9.88
P7 × P11	8.94	3.16	3.6	14.85	18.69	-9.28	-52.57	-0.40	-8.04	-0.37	-33.74	0.61	15.44

*, ** represent significant at 5% and 1% level, respectively;
DPE- Days to panicle exertion, PHT- Plant height, DMT- Days to maturity, TPP- Tillers per plant, ETP- Effective tillers per plant, NET- Non effective tiller per plant, FGP- Filled grain, EGP- Empty grain, PLT- Panicle length, GLT- Length of grain, GBD- Breadth of grain, TSW- 1000-Seeds weight, YPP- Yield per plant.

could be due to the significant heterosis observed in component traits *viz*. productive tillers per plant, panicle length, grains per panicle, grain length, grain breadth, and 1000-grain weight. Heterosis observed in the hybrids and inbreeding depression indicated fixation of additive genes in the progenies for respective traits.

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REFERENCES

Abdullah, N.S., Abdullah, M.Y., Ghaffar, M.B.A., Awal, A., Aziz, N.A. and Abdullah, S. 2018. Traits performance and heterosis estimation in F_1 rice generations crossed between basmati 370 and selected Malaysian rice varieties. *Pertanika Journal of Tropical Agricultural Science,* **41**(3): 1033-1045.

Amirtham, D. and Radha, P. 2023. Comparative Nutritional Analysis of Selected Traditional and TNAU Released Rice Varieties to Identify Nutritionally Potent Landraces for Enhancing Food Security. *Madras Agric. J.*, **110**(4-6): 1-8. [Cross Ref]

Anandakumar, C. R. and Rangasamy, S.R. 1986. Heterosis and inbreeding depression in rice. *Oryza*, **23**: 96-101.

BRRI. 2018. Adhunik Dhaaner Chash. Bangladesh Rice Research Institute, 21st edition, P-33.

Basavaraja, P., Rudraradlya, M. and Kulkarni, R.S. 1998. Genetic variability, correlation and path analysis of yield components in two F_4 population of fine grain rice. *Mysore Journal of Agricultural Sciences,* **31**(1): 1-6.

BBS. 2022. Statistical Year Book of Bangladesh 2021. Bureau of Statistics. Ministry of Planning, Govt. People's Republic of Bangladesh, Dhaka, Bangladesh.

Belaj, A., Satovic, Z., Rallo, L. and Trujillo, I. 2002. Genetic diversity and relationships in olive (*Olea europaea* L.) germplasm collections as determined by randomly amplified polymorphic DNA. *Theoretical and Applied Genetics*, **105**(4): 638-644. [Cross Ref]

Bhattacharya, J., Saha, N.K., Mondal, M.K., Bhandari, H. and Humphreys, E. 2019. The feasibility of high yielding aus-aman-*rabi* cropping systems in the polders of the low salinity coastal zone of Bangladesh, *Field Crops Research*, **234**: 33-46. [Cross Ref]

Bhattarai, M., Kamimukai, M., Rana, B.B., Oue, H., Matsumura, S. and Murai, M. 2021. A dwarfing gene sd1-d (*Dee-geo-woo-gen* dwarf) on lodging resistance and related traits in rice. *Journal of Nepal Agricultural Research Council,* **7**: 1-9. [Cross Ref]

Devi, K. R., Chandra, B.S., Hari, Y. and Venkanna, V. 2018. Heterosis and inbreeding studies for agronomic and quality traits in rice (*Oryza sativa* L.). *Agricultural Science Digestion*, **38**(4): 313-318. [Cross Ref]

FAOSTAT. 2024. FAOSTAT (http://faostat.fao.org), Food and Agriculture Organization, Rome, Italy.

Kahani, F. and Hittalmani, S. 2015. Genetic analysis and traits association in F_2 intervarietal populations in rice under aerobic condition. *Journal of Rice Research*, **3**(4): 1- 5. [Cross Ref]

Khan, M.N.A., Murayama, S., Ishimine, Y., Tsuzuki, E., Motomura, K. and Nakamura, I. 1998. Growth and yield in F_1 hybrids of rice (*Oryza sativa* L.). *Japanese Journal of Tropical Agriculture*, **42**(4): 263-271. [Cross Ref]

Khush, G.S. 2013. Strategies for increasing the yield potential of cereals: case of rice as an example. *Plant Breeding*, **132**(5): 433-436. [Cross Ref]

Kumar, S., Kumar, S., Pratap, N. and Dwivedi, D.K. 2012. Estimation of heterosis for grain yield and yield attributing traits in rice. *Plant Archives*, **12**(1): 159-164.

Mamun, M. A., Nihad, S. A. I., Sarkar, M. A. R., Aziz, M. A., Qayum, M. A., Ahmed, R., Rahman, N. M. F., Hossain, M. I. and Kabir, M. S. 2021. Growth and trend analysis of area, production and yield of rice: A scenario of rice security in Bangladesh. *PLOS One*, **16**(12): e0261128. [Cross Ref]

Murayama, S. and Sarker, M.A.Z. 2002. Agronomic performance of F_1 hybrids of rice (*Oryza sativa* L.) in Japonica-Indica crosses. *Plant Production Science*, **5**(3): 203-210. [Cross Ref]

Panse, V.G. and Sukhatme P.V. 1957. Genetics of quantitative characters in relation to plant breeding. *Indian Journal of Genetics*, **17**(2): 318-328.

Parihar, A. and Pathak, A.R. 2008. Combining ability and heterosis for yield and yield component traits in rice. *Indian Journal of Crop Science*, **3**(1): 169-171.

Ramakrishna, T., Krishna, L., Mohan, Y.C., Shankar, V.G. and Naik, D.S. 2023. Heterosis studies for grain yield and yield attributes in rice *Oryza sativa*. L hybrids. *Electronic Journal of Plant Breeding*, **14**(1): 279-295. [Cross Ref]

Sarkar, A., Roy, S.K., Vishnupriya, S., Chakraborty, M., Hijam, L., Umamaheswar, N., Rout, S., Bharti, S., Thapa, B. and Das, S. 2024. Comparison of residual heterosis in F_2 and F_3 segregating generations of Indian Mustard [*Brassica juncea* L. Czern andamp; Coss.] crosses. *Electronic Journal of Plant Breeding*, **15**(3): 546-555. [Cross Ref]

Savitha, P. and R.U. Kumari. 2015. Genetic Variability Studies in F2 and F3 Segregating Generations for Yield and its Components in Rice (*Oryza sativa* L.). Indian Journal of Science and Technology, 8(17): 1-7. [Cross Ref]

Shelley, I.J., Nosaka, M.T., Nakata, M.K., Haque, M.S. and Inukai, Y. 2016. Rice cultivation in Bangladesh: Present Scenario, Problems, and Prospects. *J. Intl. Cooper. Agric. Dev.*, **14**: 20-29.

Singh, R.K. and Chaudhary, B.D. 1985. Biometrical Methods in Quantitative Genetic Analysis. Kalyani.

Singh, R.P. 1980, Association of grain yield and its components in F_1 and F_2 population of rice. *Oryza*, **17**(3): 200-204.

Singh, B.S. and Patel, V.P. 2021. Study of heterosis and inbreeding depression in F_2 generation of upland rice (*Oryza sativa* L.). *The Pharma Innovation Journal*, **10**(5): 655-660.

Singh, S.P., Singh, R.R., Singh R.P. and Singh R.V. 1980. Heterosis in rice. *Oryza,* **17**: 109- 113.

Talebi, E., Subramanya, G., Bakkappa, S. 2010. An investigation on heterosis and inbreeding depression in the Silkworm (*Bombyx mori* L.). *ARPN Journal of Agricultural and Biological Science,* **5**: 52-55.

Tiwari, D.K., Pandev, P., Giri, S.P. and Dwivedi, J.L. 2011. Heterosis studies for yield and its components in rice hybrids using CMS system. *Asian Journal of Plant Science*, **10**: 29-42. [Cross Ref]

Venkatesan, M., Anbuselvam, Y., Murugan, S. and Palaniraja, K. 2008. Heterosis for yield, its components and traits in rice (*Oryza sativa* L.). *Oryza,* **45**(1): 76-78.

Yuan, L.P. 2009. Progress in breeding super hybrid rice. In: Xie F, Hardy B, editors. Accelerating hybrid rice development. Los Banos, Philippines: International Rice Research Institute. **4**: 3-8.