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Heterosis Breeding in Rice (*Oryza sativa* L.)

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Summary. Studies conducted at the International Rice Research Institute (IRRI) during 1980 and 1981 have shown up to 73% heterosis, 59% heterobeltiosis and 34% standard heterosis for yield in rice. The latter was estimated in comparison to commercial varieties: IR36 and IR42 (yield 4–5 t/ha in wet season trials and 7–8 t/ha in dry season trials). Generally speaking, absolute yield was lower and extent of standard heterosis was higher in wet season than in dry season with some exception. Yields up to 5.9 t/ha (22% standard heterosis) in the wet season and 10.4 t/ha (34% standard heterosis) in the dry season were obtained. Most of the hybrids performed better in some season while some performed better in both seasons. Hybrids showed better lodging resistance although they were 5–10 cm taller. F_1 hybrids had significant positive correlations with the parental traits viz., yield (r = 0.446), tillering (r = 0.746), height (r = 0.810) and flowering (r = 0.843). Selection of parents among elite breeding lines on the basis of their per se yield performance, diverse origin and resistance to insects and diseases should give heterotic combination. Yield advantage of hybrids was due primarily to increase in number of spikelets per unit area even though tiller number was reduced. Grain weight was either the same or slightly higher. High yielding hybrids also showed significant heterosis and heterobeltiosis for total dry matter and harvest index. For commercial utilization of heterosis in rice, effective male sterility and fertility restoration systems are available and up to 45% natural outcrossing on male sterile lines has been observed. Consequently, F_1 rice hybrid have been successfully developed and used in China. Prospects of developing hybrid rice varieties elsewhere appear bright especially in countries that have organized seed production, certification and distribution programs and where hybrid seed can be produced at a reasonable cost.

Key words: Hybrid vigour – Hybrid rice – Heterosis – Heterobeltiosis – Standard heterosis

Introduction

Heterosis in rice was first reported by Jones (1926) who observed marked increase in culm number and grain yield in some F_1 hybrids in comparison to their parents. Since then, several rice researchers have reported the occurrence of this phenomenon for various agronomic traits such as yield, grain weight, grains per panicle, panicles per plant, plant height, days to flower, etc. (Virmani et al. 1981). Suggestions to exploit heterosis commercially by developing F_1 rice hybrids were made from time to time (Stansel and Craigmiles 1966; Shinjyo and Omura 1966; Yuan 1966, 1972; Craigmiles et al. 1968; Watanabe 1971; Athwal and Virmani 1972; Carnahan et al. 1972; Swaminathan et al. 1972). Several cytoplasmic-genetic male sterile lines were developed for this purpose (Shinjyo and Omura 1966; Erickson 1969; Athwal and Virmani 1972; Carnahan et al. 1972) but the difficulties involved in hybrid seed production in this strictly self-pollinated crop discouraged most of these researchers in continuing research on this breeding approach.

In 1977, however, rice scientists throughout the world were surprised when Chinese scientists reported successful development and cultivation of F_1 rice hybrids in China (IRRI 1977). By then, hybrid rice varieties had already occupied about two million hectares of rice lands in this country. These varieties had shown 20–30% higher yield than conventionally bred rice varieties and were found to possess wider adaptability (Lin and Yuan 1980). Since then, the area under hybrid rice in China has increased to 6 million ha (about 17% of the total rice area) resulting in an increased production of about 4 million tons annually.

The International Rice Research Institute (IRRI) had initially conducted studies on hybrid rice during 1970 to 1972 when a cytoplasmic male sterile line, derived from Taichung (Native) 1 cytoplasm and in the genetic background of an Indian variety: Pankhari 203,

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was developed. Encouraged by the success of hybrid rice in China hybrid breeding research at IRRI was revived in 1979 (IRRI 1980) to explore its potentials and problems under tropical conditions. This program has three major components:

1. Heterosis studies
2. Male sterility and fertility restoration systems and
3. Natural outcrossing on male sterile lines and techniques of hybrid seed production.

In this paper, we present results of heterosis studies conducted at IRRI during the past two years and discuss the current outlook on heterosis breeding in this strictly self-pollinated cereal crop.

Materials and Methods

Experiment I – 1980 Dry Season

Sixteen F_1 hybrids involving two male sterile lines from China (Zhen Shan 97A and V20A), their maintainer lines 97B and V20B, and a few elite IRRI lines (designated as IR) were evaluated in an unreplicated observational yield nursery. Each F_1 hybrid was planted adjacent to its parents. The two leading commercial Philippine varieties viz., IR36 and IR42 were included as checks. Twenty-one days old seedlings were transplanted in the field at 20 cm × 20 cm spacing in plots measuring 1.2 m × 2.8 m. One seedling was planted to each hill. Fertilizer was applied at 120-30-0 (N-P-K) kg per ha. Recommended insect control measures were used to control major insect pests. Observations were made on days to 50% flowering, and yield (estimated from 1 m_2 net area).

Experiment II – 1980 Wet Season

A total of 49 F_1 hybrids were evaluated by grouping them into four sets. The crosses were made by using two cyto-sterile lines from China (Zhen Shan 97A, V20A) and a few IR elite lines as female parents, and several identified restorers (viz., IR28, IR20, IR50 and IR54) and other elite lines selected from IRRI's on-going breeding program as male parents. The isogenic maintainer lines 97B and V20B along with the parents involved in the respective hybrids were included for comparison. The commercial varieties IR36 and IR42 were planted in all sets to serve as checks. The plots were arranged in the field in a randomized complete block design with three replications. One seedling was planted per hill. Plot size was 1.4 m × 5.8 m. The spacing, fertilizer application and insect control were the same as for Experiment I. Information on days to 50% flowering, plant height and extent of lodging was recorded. Data on yield were collected from a net area of 3 m^2 while the particulars on yield components and physiological characters were based on samples from 1 m^2.

Experiment III – 1981 Dry Season

A total of 62 F_1 hybrids including 49 hybrids evaluated in Experiment II were evaluated in four groups. The respective parents of the hybrids were planted in the corresponding groups for comparison. Commercial varieties IR36, IR42 and IR54 were included as checks. Plot size, spacing and insect control were the same as for Experiment II. One seedling was planted to each hill. Fertilizer was applied at 120-30-30 (N-P-K) kg/ha. Plots were arranged in the field in a randomized complete block design with three replications. Data were recorded on date of 50% flowering, plant height and lodging. Grain yield was collected from a net area of 5 m^2 and yield component analysis based on samples from 1 m^2.

The F_1 hybrid performance was evaluated on the basis of the estimates of heterosis (Matzinger et al. 1962), heterobeltiosis (Fonseca and Patterson 1968), and standard heterosis (comparison of F_1 with the best commercial variety).

Data from the replicated tests (Experiments II and III) were analyzed, and correlation and regression coefficients for some traits were computed using standard statistical procedures.

Results

Experiment I – 1980 Dry Season

Eight of the sixteen F_1 hybrids showed positive heterosis (18–59%), heterobeltiosis (5–42%) and standard heterosis (7–35%). Their yield ranged from 725 g to 932 g/m^2 while the commercial varieties: IR36 and IR42 yielded 725 and 691 g/m^2, respectively. These hybrids were all semidwarfs (75–106 cm) and had a growth duration of 100–127 days. Although these results were preliminary yet these were encouraging enough to pursue further studies on heterosis at IRRI.

Experiment II – 1980 Wet Season

In one of the four sets including five hybrids (Table 1) significant positive heterosis (up to 73%), heterobeltiosis (up to 59%), and standard heterosis (up to 25%) for yield were observed. Three of the five hybrids significantly outyielded the commercial variety IR42 by a margin of 713 to 1,055 kg/ha. The experimental hybrid V20A/IR50 showed the highest standard heterosis. The hybrids also showed better lodging-resistance than their parents inspite of their slightly taller stature (Table 2). Stronger root system and thicker culm of the hybrids (Lin and Yuan 1980) may be responsible for their lodging resistance. The high yielding hybrids flowered in 71–91 days indicating that growth duration did not limit the yield potential of hybrids.

Among the remaining three sets of hybrids evaluated during 1980 wet season, seven showed significant standard heterosis and heterobeltiosis for yield (Table 3). These hybrids flowered in 79–93 days after seeding. Some of these yielded up to 1.1 t/ha higher than the best commercial variety. Hybrids also tended to show more earliness than their parents but their height was either comparable or slightly taller than their parents in the tropics.

Experiment III – 1981 Dry Season

Out of the 62 hybrids evaluated for yield in four different sets in the 1981 dry season, 42 showed sig-

Table 1. Heterosis, heterobeltiosis and standard heterosis for grain yield in five F_1 rice hybrids. IRRI, 1980 wet season (Virmani et al. 1981)

Hybrid	Yield (t/ha)	Heterosis (%)	Heterobeltiosis (%)	Standard heterosis over (%)	
				IR36	IR42
Set I					
V20A/IR50[a]	5.2	+59**	+28**	+29**	+25**
97A/IR54[a]	5.2	+73**	+59**	+28**	+24**
V20A/IR40	4.9	–	–	+20*	+17*
V20A/IR54[a]	4.6	+59**	+42**	+14	+10
V20A/IR28[a]	4.0	+31**	+12	– 3	– 5

* Significant at 5% level; ** Significant at 1% level
[a] Better parent

Table 2. Yield and some agronomic characteristics of F_1 hybrids in comparison to their parents and check varieties grown in a replicated yield trial. IRRI, 1980 wet season

Hybrid/ variety	Yield (t/ha)	Days to 50% flowering	Height (cm)	Lodging percentage at growth stages[a]			
				4	6	7	9
F_1 hybrids:							
V20A/IR50	5.2	71	118	0	0	15	95
97A/IR54	5.2	91	126	0	0	0	75
V20A/IR40	4.9	89	117	0	0	0	5
V20A/IR54	4.6	90	125	0	0	0	5
V20A/IR28	4.0	72	117	0	0	0	85
Mean	4.8	83	121	0	0	3	53
Parents:							
IR50	4.1	75	117	0	0	95	100
IR28	3.5	75	121	0	0	50	100
IR54	3.3	97	121	15	25	40	100
97B	2.7	67	112	0	0	0	0
V20B	2.5	69	110	0	0	0	0
Mean	3.2	77	116	3	5	37	60
Commercial varieties:							
IR42	4.2	105	118	0	0	0	100
IR36	4.1	83	102	0	35	100	100
Mean	4.1	94	110	0	18	50	100

[a] 4 = booting; 6 = 50% flowering; 7 = dough; 9 = maturity

nificant heterosis (12.6 to 58.4%) out of which 23 showed significant heterobeltiosis (11.2 to 48.6%). Nine of these 23 hybrids also showed significant standard heterosis (13.6 to 34.4%). Yield and some agronomic characteristics of the promising F_1 hybrids selected among the four sets of hybrids are given in Table 4. As observed in the wet season, the height of the F_1 hybrids was almost equal to or slightly taller than the parents and/or check varieties but in some hybrids lodging was less than in the check varieties. The growth duration of hybrids was generally comparable with the check varieties and in a few cases it was even earlier.

Out of a total of 127 F_1 hybrids evaluated for yield in the three crop seasons (Table 5) 71 percent showed positive heterobeltiosis (range 0.5–59%) and 57% showed positive standard heterosis (range 0.1–34.4%).

Effect of Season on Heterosis for Yield

Absolute yield and extent of standard heterosis in the F_1 hybrids were found to vary in the two crop seasons (Table 6). In general, the yields of F_1 hybrids were lower and the extent of standard heterosis was higher in wet season than in dry season. However, some

Table 3. Standard heterosis and heterobeltiosis for grain yield of some promising F_1 rice hybrids. IRRI, 1980 wet season (Virmani et al. 1981)

Hybrid	Days to flowering	Yield (kg/ha)	Standard heterosis (%)		Hetero-beltiosis (%)
			IR36	IR42	
Set 2					
IR11248-242-3[a]/IR15323-4-2-1-3	91	5923	69**	22*	35**
IR11248[a]/IR19672-19-3	93	5500	57**	14	25*
IR11248[a]/IR15324-117-3-2-2	80	5399	54**	12	23*
Set 3					
IR10154-23-3-3/IR54[a]	79	5637	21*	20	50**
IR747B2-6-3/IR54[a]	81	5500	18	17	46**
IR10154-23-3-3/IR2797-105-2-2-3[a]	81	5022	8	7	31*
Set 4					
IR11248-242-3-2/IR9828-41-2-1[a]	89	5322	22	60**	28*

*, ** Significant at the 5% and 1% levels, respectively
[a] Better parent

Table 4. Yield and some agronomic characteristics of some promising F_1 rice hybrids. IRRI 1981 dry season

Hybrid	Yield (t/ha)	Vigour 30 DAT[a]	Plant height (cm)	Days to 50% flowering	Lodging (%)
Set 1					
IR11248-242-3-2/IR2823-103-5-1	8.9	2	104	93	17
IR11248/IR13525-97-1-1-3	8.8	2	99	94	25
IR36, check	7.4	4	90	87	25
IR54, check	7.2	2	108	95	100
Set 2					
IET 3257/IR2797-105-2-2-3	10.4	2	123	100	0
IET 3257/IR54	10.3	1	113	87	30
IR36, check	7.7	2	89	85	0
IR54, check	7.8	2	110	92	30
Set 3					
IR11248-242-3-2/IR2823-399-5-6	9.2	4	106	94	100
IR11248/IR13188-9	9.0	2	98	87	0
IR11248/IR9224-23-2-2	9.0	3	95	84	0
IR36, check	7.9	4	89	87	90
IR54, check	7.4	3	110	94	100
Set 4					
IR11248-242-3-2/IR15324-117-3-2	9.3	2	109	94	100
IR34/IR2797-125-3-2-2-2	9.1	2	112	87	90
IR36, check	8.0	3	89	86	60
IR54, check	7.5	2	107	93	100

[a] 1 = Extra vigorous; 3 = Vigorous; 5 = Plants intermediate or normal
DAT = Days after transplanting

hybrids maintained both higher absolute yield and higher standard heterosis in the dry season also. Most of the hybrids performed better in one season only while some performed better in both seasons. The highest yielding hybrids in the two crop seasons viz., IET 3257/IR2797-105-2-2-3 (in 1981 dry season) and IR11248-242-3-2/IR15323-4-2-1-3 (in 1980 wet season) were season specific.

Correlation Between F_1 Mean and Parents

The relationship between the performances of the hybrids and their corresponding midparent and better parent, was assessed by working out the correlation and linear regression coefficient for four characters namely yield, tillering, plant height, and days to 50% flowering, from the 1981 dry season data. The results

Table 5. Summary of experiments on heterosis for grain yield in rice conducted at IRRI, 1980 – 1981

Experiment	Total No. of hybrids studied	Positive heterobeltiosis		Positive standard heterosis	
		No. of hybrids	Range (%)	No. of hybrids	Range (%)
Dry season, 1980	16	8	5.0 – 42.0	5	7.0 – 29.0
Wet season, 1980					
Set 1	5	4	12.0 – 59.0	3	3.0 – 13.0
Set 2	25	11	1.4 – 28.0	8	1.4 – 22.0
Set 3	9	7	10.8 – 34.9	8	0.5 – 22.4
Set 4	10	7	4.0 – 50.0	3	7.0 – 20.0
Dry season, 1981					
Set 1	15	11	0.5 – 15.1	14	0.1 – 19.5
Set 2	18	14	0.6 – 48.6	11	1.4 – 34.4
Set 3	15	14	4.3 – 20.8	12	4.2 – 16.3
Set 4	14	14	11.8 – 27.4	9	4.2 – 17.0
Total	127	90 (71%)	0.5 – 59.0	73 (57%)	0.1 – 34.4

Table 6. Standard heterosis for grain yield of some promising F_1 rice hybrids. IRRI, 1980 – 1981

Hybrid	1980 Wet season			1981 Dry season		
	Yield (t/ha)	Standard heterosis (%)		Yield (t/ha)	Standard heterosis (%)	
		IR36	IR42		IR36	IR42
V20A/IR50	5.2	+29**	+25**	7.6	– 2	+ 1
97A/IR54	5.2	+28**	+24**	7.6	– 2	+ 1
IR11248-242-3-2/IR15323-4-2-1-3	5.9	+69**	+22**	8.8	+11	+17*
IR11248-242-3-2/IR19672-19-3	5.5	+57**	+14	8.9	+12	+17*
IR11248-242-3-2/IR15324-117-3-2-2	5.4	+54**	+12	9.3	+17*	+23**
IR10154-23-3-3/IR54	5.6	+21*	+20	7.8	+ 1	+ 3
IR747B2-6-3/IR54	5.5	+18	+17	8.2	+ 6	+ 9
IR11248-242-3-2/IR9828-41-2-1	5.4	+22	+60**	8.9	+12	+17*
IR11248-242-3-2/IR13525-97-1-1-3	3.7	–23	+12	8.8	+17**	+20**
IET 3257/IR2797-105-2-2-3	4.0	–13	–15	10.4	+34**	+39**
IET 3257/IR54	4.3	– 6	– 8	10.3	+33**	+37**
IR11248-242-3-2/IR2823-399-5-6	4.9	– 8	+36**	9.2	+16*	+22**
IR11248-242-3-2/IR9224-223-2-2	4.8	+ 9	+45**	9.0	+14*	+19**
IR11248-242-3-2/IR13188-9	4.2	– 4	+27**	9.0	+14*	+19**

* Significant at 5% level; ** Significant at 1% level

Table 7. Simple correlation (r) and regression coefficients (b) and intercept (a) between F_1 rice hybrids and their parents. IRRI, 1981 dry season

Character	Mid parent			Better parent		
	r	b	a	r	b	a
Yield	0.446**	0.536	4.5	0.372**	0.530	4.3
Tillering	0.746**	0.603	5.2	0.636**	0.424	7.5
Height	0.810**	0.828	18.5	0.655**	0.611	36.5
Days to 50% flowering	0.843**	0.884	4.4	0.677**	0.732	15.0

** Significant at 1% level

Table 8. Heterosis (upper row), heterobeltiosis (middle row) and standard heterosis[a] (lower row) for yield, and yield components in some rice hybrids. IRRI, 1980 wet season (Virmani et al. 1981)

Hybrid	Yield gm/m²	Heterosis, heterobeltiosis and standard heterosis (%)							
		Yield	Panicles /m²	Spikelets /panicle	Total spikelets /m²	Spikelet fertility (%)	1000-grain wt. (gm)	Total dry matter	Harvest index
V20A/IR50[b]	596	+60**	−6[ns]	+19*	+13[ns]	+16[ns]	+20*	+24**	+30**
		+30**	−27**	+12[ns]	−7[ns]	+4[ns]	+7*	+19*	+9[ns]
		+13*	−24**	+27**	+4[ns]	−8[ns]	+17*	+5[ns]	+7[ns]
97A/IR54[b]	542	+47**	−12[ns]	+31**	+17*	+11[ns]	+10*	+24**	+21*
		+20*	−21*	+18*	+17*	−2[ns]	0	+13*	+5[ns]
		+3[ns]	−41**	+54**	−10[ns]	−3[ns]	+15*	+14*	−9[ns]
V20A/IR54[b]	540	+46**	−7[ns]	+30**	+22*	+10[ns]	+5[ns]	+23**	+19*
		+20*	−17*	+19*	+18*	−5[ns]	+2[ns]	+12*	+5[ns]
		+3[ns]	−38**	+47**	−9[ns]	−6[ns]	+17*	+12*	−9[ns]
V20A/IR28[b]	480	+39**	+7[ns]	+10[ns]	+21*	+9[ns]	+9*	+19*	+20*
		+20*	−8[ns]	+2[ns]	+12[ns]	+2[ns]	+8*	+19*	+2[ns]
		−9[ns]	−25**	+25**	−6[ns]	−17*	+19*	−4[ns]	−4[ns]

* Significant at 5% level; ** Significant at 1% level
[ns] Non-significant
[a] Determined over IR36
[b] Better parent

(Table 7) indicated that for all the four traits the F_1 values had positive correlation with the midparent and better parent values. But the estimates of correlation coefficient (r) relating to better parent were lower than those of mid parent for all the four characters. The results of regression estimation also revealed that hybrid values regressed relatively nearer to mid-parental value than to the better parent values.

Yield Component Analysis

From a set of hybrids evaluated in 1980 wet season observations were also recorded on yield, yield components (tillers per m², spikelets per panicle, spikelet per m² and 1,000 grain weight), total dry matter and harvest index (Table 8). Heterosis values for yield ranged from 39 to 60% while heterobeltiosis ranged from 20 to 30%; standard heterosis estimated in comparison to variety IR36 was rather low (−9 to 13%). Heterosis in yield was mainly due to the increase in number of spikelets per panicle and the heavier 1,000 grain weight of the hybrids. The hybrids, however, were inferior to their parents and the commercial varieties in panicle number per unit area. This reduction in tillering in F_1s was over-compensated by the increase in their number of spikelets per panicles and consequently hybrids showed positive heterosis for spikelets/m². Significant heterosis and heterobeltiosis were also observed for total dry matter. For harvest index, significant heterosis was exhibited by the hybrids but heterobeltiosis and standard heterosis for all the hybrids were non-significant.

Discussion

These studies have clearly shown the occurrence of significant heterosis, heterobeltiosis, and standard heterosis in rice under tropical conditions. The increase in yield of F_1 hybrids showing significant standard heterosis in the replicated yield trials ranged from 0.7 to 1.1 t/ha in the wet season and 1.1 to 2.5 t/ha in the dry season. Yields up to 5.0 t/ha with 22% standard heterosis were obtained in the wet season and up to 10.4 t/ha (standard heterosis 32%) in the dry season. The high yield as well as high frequency of heterotic F_1 hybrids in these trials may be attributed to their parents which were specifically selected among the conventionally bred elite lines on the basis of their higher per se yield performance, diverse origin and/or resistance to disease and insects.

The significant positive correlation of the performance of the hybrids with that of the mean of the parents and better parent indicated that the expression of heterosis in F_1s in rice is primarily dependent on the potential worth of their parents, for the characters concerned. However, the relatively lower estimate of 'r' in hybrid vs better parent may perhaps reveal that the high per se performance of one of the parents of a hybrid alone is inadequate for the expression of hybrid vigor. As observed in the present study, a high correlation between hybrid performance and mid-parental value can generally be expected when the hybrid vigor expression is predominantly contributed by additive and additive × additive gene effects. The corresponding regression estimates in this study did not deviate significantly from 1.0 which is an indication of the negligible role of non-additive gene action for the high expression of F_1s. This is not unexpected in self pollinated crops like rice. However, only in two instances in this experiment both the parents of the highest yielding hybrid (above 10 t/ha) had only average expression of yield per se (6.5–7 t/ha). This may be attributed to the role of non-additive effects for the expression of hybrid vigor. Such effects for yield in F_1 hybrids have also been reported by Khaleque et al. (1977), Kumar and Saini (1980), and Parmar (1974). We, therefore, believe that heterosis breeding can supplement the conventional breeding program by utilizing both additive and non-additive effects to increase varietal productivity in rice.

Some of the high yielding hybrids (including the highest yielding) showed specificity to the season, while some had consistently superior performance in both the seasons. It should, therefore, be possible to develop high yielding hybrids specific as well as non-specific to the seasonal influence.

The hybrids have also shown significant heterosis for total dry matter and harvest index but heterobeltiosis and standard heterosis for these traits were significant only in some crosses. However, for spikelet number per panicle, all these crosses exhibited significant heterosis, heterobeltiosis and standard heterosis. It, therefore, appears that heterosis influences an increase in the size of source as well as sink in the rice plant. Superiority of F_1 hybrids with regard to physiological traits namely: photosynthetic area, chlorophyll content per unit area, photosynthetic efficiency, mitochondrial activity and root-activity, etc. had also been reported in China (Lin and Yuan 1980) and elsewhere (McDonald et al. 1971). Virmani et al. (1981) have, therefore, postulated that yield increase in rice varieties developed so far through conventional breeding has been brought about primarily by improvement in plant type and that further improvement in their yield potential should be possible by increasing their physiological efficiency. Heterosis breeding is considered practical in combining improved plant type with increased physiological efficiency to develop rice varieties with higher yield potential.

Hybrid rice has also been found to have stronger and more active root system and early seedling and vegetative vigour (Lin and Yuan 1980). The F_1 hybrids have shown higher tolerance for salinity than their parents (Akbar and Yabuno 1975) and are more efficient in utilizing applied fertilizer (Lin and Yuan 1980). Their strong and deep root system should also impart drought tolerance. Hybrid rice should, therefore, also have potential in rainfed lowland and uplands. Our preliminary observations in this regard are positive and encouraging.

Besides being higher yielding, hybrid rice varieties in China have shown wider adaptability to photoperiod and temperature variations (Lin and Yuan 1980). Athwal and Virmani (1972) had suggested that hybrid breeding should enable expeditious incorporation of disease and insect resistance governed by dominant genes. In China, resistance to brown planthopper and bacterial leaf blight was incorporated easily in the hybrids using IR26 as the restorer parent (Lin and Yuan 1980).

Current Outlook

Essential pre-requisites to the commercial exploitation of heterosis in rice are:

- Availability of effective male sterility and fertility restoration system(s).
- Sufficient natural outcrossing on male sterile plants by restorer lines to enable bulk production of hybrid seeds.

A number of effective cytoplasmic male sterile, maintainer and restorer lines are available in rice (Lin and Yuan 1980; Virmani et al. 1981) and sufficient (up to 45%) natural outcrossing can occur on male sterile rice plants (Lin and Yuan 1980; Virmani et al. 1980). Hybrid seed production techniques have been already developed in China (Lin and Yuan 1980) and hybrid seed yields of 750–1,000 kg/ha are being obtained in the commercial seed production plots. These techniques are also being adopted at IRRI with encouraging results (Virmani et al. 1981).

The cost of hybrid seed in China is ten times the cost of non-hybrid seed but the seed rate of hybrid rice is 1/4th to 1/5th of the conventional rice varieties. Thus, the hybrid rice cultivators spend about 2–3 times extra ($ 20–25/ha) on seed than the cultivators of conventionally bred rice varieties. The extra yield of hybrid rice in China is about 0.75 to 1 t/ha (equivalent to $100–120) thereby resulting in benefit : cost ratio of 5 : 1. Extent of standard heterosis necessary to cover the additional cost of hybrid seed (up to $45 per hectare) has been estimated by Virmani et al. (1981). At 4–6 t/ha yield level of the hybrid about 4 percent standard heterosis would be adequate to cover the extra seed cost to $45/ha. Our results as well as those obtained in China have shown 20–30% of exploitable standard heterosis. Therefore, hybrid rice should be economically viable.

Major difficulty in adopting heterosis breeding technology in this strictly self-pollinated crop is the difficulty in production, certification and distribution of hybrid seeds. Many rice growing countries lack organized and efficient seed production, certification and distribution program. Implementation of this technology in countries outside China would depend upon (Virmani et al. 1981):

- Status of the on-going rice breeding program in the country,
- Yield level of the non-hybrid improved rice varieties,
- Farmers' awareness to increase rice production by using improved technology,
- Economics of hybrid seed production, and
- The type and efficiency of seed production, certification and distribution agencies available in the country.

Encouraged from the results reported from China and IRRI some Asian countries viz., India, Indonesia, Philippines, Bangladesh, Thailand, South Korea, and Sri Lanka have either already initiated research or shown interest in initiating research on hybrid rice. Some private seed companies in USA are also exploring the prospects of heterosis breeding in rice in collaboration with Chinese scientists.

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Literature

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