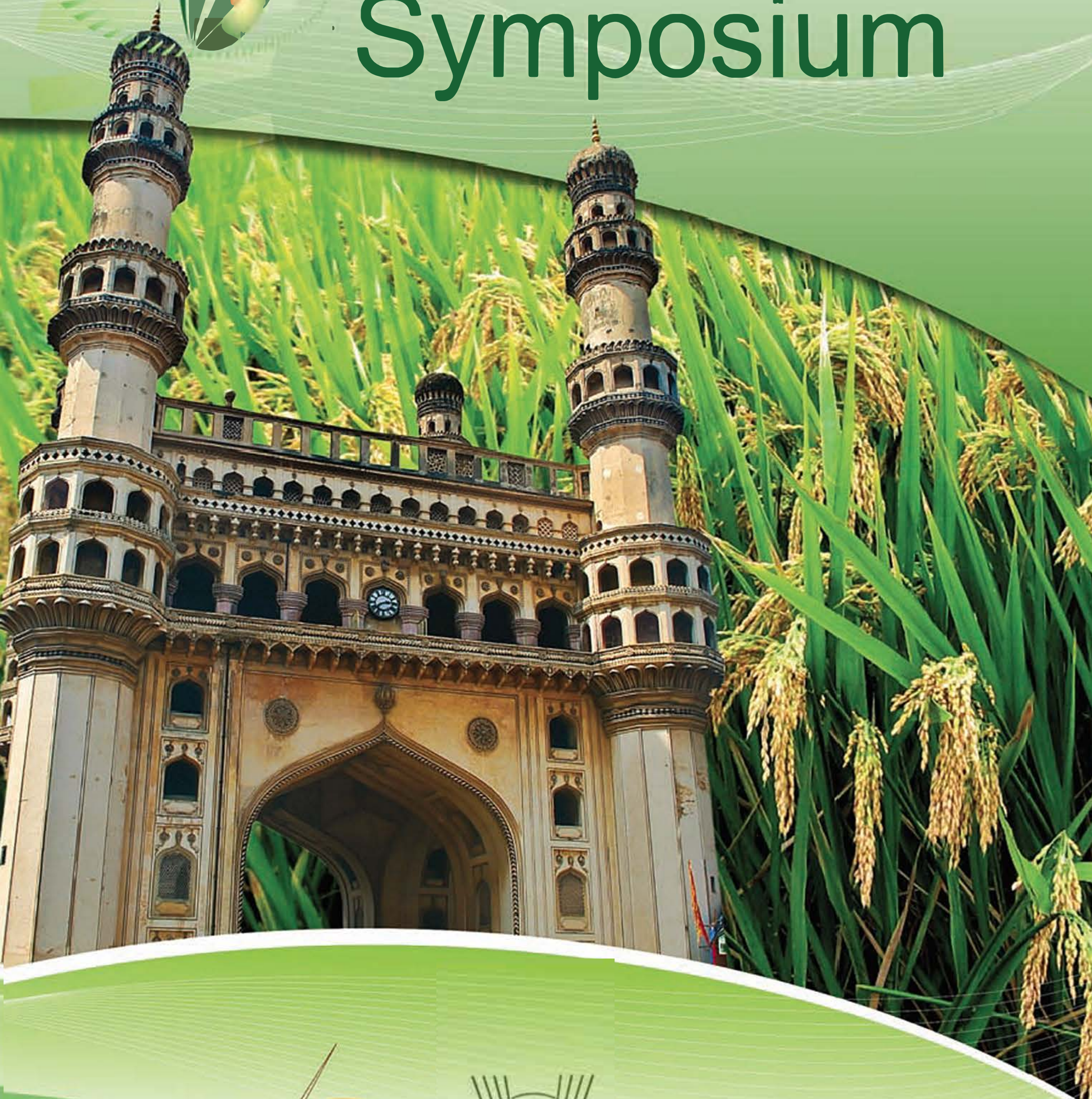
Proceedings of the 6th International Hybrid Rice Symposium



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10-12 September 2012
Hyderabad, India

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The responsibility for this publication rests with the International Rice Research Institute.

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Foreword

The agricultural sector, particularly the rice sector, is radically changing in India and the rest of the world. Rice remains the world's most important food commodity, particularly in Asia, but it faces challenges such as climate change, degradation of farming areas, decreased water availability, and increased population. It is therefore appropriate to discuss these pressing concerns as the demand for rice is increasing sharply despite dwindling resources. This reality was examined at the 6th International Symposium on Hybrid Rice with the theme "Public-Private Partnership for Hybrid Rice." The topics covered hybrid rice development, hybrid rice seed production, applications of molecular technology, crop and resource management, and the economics of hybrid rice.

The symposium was held in Hyderabad, Andhra Pradesh, India, on 10-12 September 2012. It was hosted by the Indian Council for Agricultural Research (ICAR) and jointly organized by the International Rice Research Institute (IRRI) and the Directorate of Rice Research (DRR). A total of 440 representatives from the public and private sector of 32 countries participated.

We are grateful to the government of India, the many individuals who worked on the international and national organizing committees in preparation for the symposium, and the authors who presented the papers in this publication. We gratefully acknowledge financial support provided by Bayer BioScience Pvt. Ltd.; Pioneer Hi-Bred International, Inc.; SeedWorks International Pvt. Ltd.; DCM Shriram Consolidated Ltd.; Rasi Seeds (P) Ltd.; and Advanta India Ltd. We hope that this publication will provide a valuable source of information for hybrid rice researchers, seed production and technology transfer agencies, and graduate students in plant breeding and seed technology.

Robert S. Zeigler
Director General
International Rice Research Institute

Country report: hybrid rice in Bangladesh

Helal Uddin Ahmed, Md. Jamil Hasan, Ashish Kumar Paul, Priya Lal Biswas, Umma Kulsum, Afsana Ansari, Anwara Akter, and Hafizar Rahman

Bangladesh is the fourth-largest producer and consumer of rice in the world, with an annual production ranging from 33 to 35 million tons. About 75% of the total cropped land is covered by rice and more than 60% of the labor force is engaged in rice production. Rice alone contributes around 10% to GDP. Thus, this single crop has a multiple effect on our daily life and economy (Iftekharuddaula et al 2011).

Bangladesh has made notable technological progress in rice cultivation over the last two decades, which has contributed to achieving food security despite doubling of the population and a reduction in arable land since its independence in 1971. Cereal production increased from 10.0 million tons (1971) to 35.0 million tons in 2010, thus reducing hunger and poverty, but we still face a food shortage. Today, rice has a special position as a provider to more than 75% of the Asian population and more than three billion people in the world of food that represents 50% to 80% of their daily calorie intake (Khush 2005, Amirjani 2011). Bangladesh needs to increase yield further to meet the growing demand emanating from population growth. To produce the required quantity, the only option is to increase production per unit area, as there is a scarcity of land. The increased demand for rice will have to be met with less land, less water, less labor, and less pesticide. With the shifting yield frontier in rice, one of the best options and new answers available to plant breeders is hybrid rice because of its elevated yield potential, good agronomic performance, and disease resistance. The use of rice hybrids is becoming more popular in Bangladesh day by day. This started in 1998 with a few tons and in 2008 the quantity rose to 11,000 tons, of which 2,800 tons are locally produced (Faruque 2009). Hybrid rice technology could offer considerable opportunity for increasing rice productivity in Bangladesh, where the labor-land ratio is high, labor costs are reasonably low, land is becoming scarce, and population density is increasing at an alarming rate. Therefore, to go beyond the present yield ceiling of semidwarf modern varieties, hybrid rice seems to be an attractive alternative. It is expected to have positive sociopolitical implications for the food front under Bangladeshi conditions.

Present status of hybrid rice at the Bangladesh Rice Research Institute

Hybrid rice research in Bangladesh expanded in collaboration with the International Rice Research Institute (IRRI) since 1993 and BRRI released one hybrid with the name BRRI hybrid dhan1 for the boro season in 2001. Another hybrid was recommended by the National Seed Board (NSB) in 2008 for the boro season named BRRI hybrid dhan2 for intensive cultivation in the regions of Jessore, Comilla, Dhaka, and Rajshahi. The average yield of newly released variety BRRI hybrid dhan2 was 8.0 to 8.5 t/ha. Another hybrid, BRRI hybrid dhan3, was released in 2009 for the boro season. It has tremendous yield potential and showed average yield of 8.5 to 9.0 t/ha. Both boro varieties are commercially sound for hybrid seed production in the dry season. In 2010, BRRI finally was able to release the first-ever T. aman hybrid rice variety in Bangladesh. It has yield potential of 6.0 to 6.5 t/ha with slender grain. One hybrid for the T. aman season is in the pipeline. About 10 potential CMS lines for the dry and wet season with desirable grain type and duration have been developed along with restorer lines. A specific and goal-oriented work plan has been prepared for developing heterotic rice hybrids for both the irrigated (boro) and rainfed (T. aman) ecosystems. Efforts are also being made to develop new sources of CMS lines adapted to Bangladeshi conditions. A disease-resistant source for parental lines against bacterial blight and sheath blight has also been found. About 1.0 million hectares of boro rice land were covered by exotic hybrid rice during boro 2010-11, which came mostly from China and India. It was expected that 1.2 million hectares of land would be covered by hybrid rice in the next season.

Sources of hybrid rice parental lines

BRRI is the only public-sector research institute with a mandate for conducting research on rice. Informal collaboration in hybrid rice research began between BRRI and IRRI in 1993. Initial work involved testing of F_1 hybrids and evaluating CMS lines and restorer lines from IRRI. Later, BRRI started hybrid rice breeding work for developing hybrid parental lines using germplasm from indigenous sources (the gene bank of BRRI, conventional breeding program) and international nurseries mostly from IRRI. A number of germplasm (A, B, and R) lines were also supplied by Chinese experts during their consultancy mission under the TCP project funded by FAO in 1997-98. Although the parental lines from China were not adapted to Bangladesh and were susceptible to pests and diseases, they were found to be good CMS sources. Therefore, BRRI used those CMS sources and developed some new CMS lines along with their maintainer lines. The CMS lines introduced from China were unstable in Bangladeshi conditions, so the IRRI-developed CMS lines IR58025A and IR62829A were used to develop locally adapted CMS lines. Several selected local varieties/lines were identified as maintainers and were backcrossed to their respective CMS sources. A large number of high-yielding locally developed elite lines were tested along with some good restorers from IRRI. These restorers were purified and multiplied for use in the production of experimental hybrids. BRRI also received some Indian germplasm through IRRI. For promoting hybrid rice cultivation in the country, Bangladesh should develop its own parental lines. Keeping this view in mind, BRRI has developed several A, B, and R lines by using CMS sources from other countries (Table 1). Recently, BRRI has developed quite a good number of hybrid parental lines that are being used to develop heterotic rice hybrids.

Multilocation trials of promising hybrids

Multilocation trials have been carried out to study the adaptability and yield potential of the identified hybrids. Seven promising hybrids with two checks were evaluated at five different BRRI regional stations during the T. aman season of 2010. Twenty-one-day-old seedlings were transplanted in a 30-m^2 plot following a randomized complete block (RCB) design with three replications using a single seedling per hill. Spacing was 20 × 15 cm. Fertilizers were applied at 150:100:70:60:10 kg/ha urea, TSP, MP, gypsum, and $ZnSO_4$, respectively. Among the seven tested entries, only one combination (II32A/BR15R) produced about a 1 t/ha yield advantage (20.8%) over BRRI dhan33 at four locations. The highest yield (5.33 t/ha) was recorded in Rajshahi, followed by Gazipur (5.20 t/ha) (Table 2). The lowest yield performances were observed at BRRI R/S Comilla for all the tested entries because of a severe attack of insect pests and diseases.

Six promising hybrids were evaluated at headquarters and three regional stations along with BRRI dhan28, BRRI dhan29, BRRI hybrid dhan2, and BRRI hybrid dhan3 as checks. Thirty-day-old seedlings were transplanted in 30-m^2 plots following an RCB design with three replications using a single seedling per hill. Spacing was 20 × 15 cm. Fertilizers were applied at 270:130:120:70:10 kg/ha urea, TSP, MP, gypsum, and $ZnSO_4$, respectively.

Results showed that the overall yield performance of ten entries was better at Comilla, followed by Barisal station (Table 3). Among the test hybrids, II32A/BR12R (9.2 t/ha) produced the highest yield, followed by BR10A/BR12R (9.0 t/ha) at Comilla. At Barisal, the check BRRI hybrid dhan3 exhibited the highest yield (10.15 t/ha). The average yield advantage of the test hybrids was not observed to be acceptable. Therefore, none of the hybrids was selected for further evaluation.

CMS seed multiplication

Seed production is another important constraint in hybrid rice. The effect of several seed production components on outcrossing rate and seed yield of CMS lines was studied during T. aman 2010 and boro 2011. Three CMS lines (BR10A, BR11A, and IR58025A) along with their maintainers were grown as parental materials. Maintainer lines were sown on three different dates at 3-day intervals and CMS lines were sown along with a second set of their respective maintainer lines. Some 20 g/m^2 of seeds were sown in the seedbed. Twenty-one-day-old seedlings were transplanted at a spacing of 15 cm × 15 cm having a ratio of 2:6 of B and A lines. Fertilizers at 150:100:70:60:10 kg/ha of urea, TSP, MP, gypsum, and zinc sulfate were used, of which ¼ urea, a full dose of TSP, gypsum, $ZnSO_4$, and $^2/_3$ MP were applied as basal. The remaining urea with equal splits was applied at 15–20 days after transplanting (DAT), 35–40 DAT,

Table 1. A, B, and R and local lines used in hybrid rice development in Bangladesh (2002-11).

Designation	Cyto source	Country of origin	Restorer line	Source
Jin23A/B	WA	China	Gui99R	China
Gan 46 A/B	Dissi	China	Ajay R	India
II 32 A/B	ID	Indonesia	PMSRI-17-4-B-13	India
IR68886A/B	WA	IRRI	IR52713-2B-8-2B-1-2	IRRI
IR68888 A/B	WA	IRRI	IR65209-3B-6-3-1	IRRI
IR68897A/B	WA	IRRI	IR65610-38-2-4-2-6-3	IRRI
IR70960 A/B	Gambiaca	IRRI	IR44675R	IRRI
IR 75595 A/B	Dissi	IRRI	IR71137-328-2-3-3-2R	IRRI
IR75608 A/B	Dissi	IRRI	IR69713-3-2-1-3-2R	IRRI
IR77801 A/B	Dissi	IRRI	IR69702-91-2-3R	IRRI
IR 77805 A/B	Dissi	IRRI	IR73885-10-4-3-2-1-6R	IRRI
IR58025 A/B	WA	IRRI	IR65482-7-216-1-2R	IRRI
IR79128 A/B	WA	IRRI	IR69713-127-2-1-3-2R	IRRI
IR 79156 A/B	WA	IRRI	BR 827R	BRRI
IR 80151 A/B	WA	IRRI	BR 168 R	BRRI
IR 80154 A/B	Gambiaca	IRRI	BR 736R	BRRI
IR 80156 A/B	Kalinga	IRRI	BR6839-41-5-1R	BRRI
BR1A/B	WA	BRRI	BR7013—62-1-1R	BRRI
BR2A/B	WA	BRRI	BR7011-37-1-2R	BRRI
BR3A/B	WA	BRRI	BR 6723-1-1-2R	BRRI
BR4A/B	WA	BRRI	BR10R	BRRI
BR5A/B	WA	BRRI	BR11R	BRRI
BR6A/B	WA	BRRI	BR12R	BRRI
BR7A/B	WA	BRRI	BR13R	BRRI
BR8A/B	WA	BRRI	BR14R	BRRI
BR9A/B	Gambiaca	BRRI	BR15R	BRRI
BR10A/B	WA	BRRI	BR16R	BRRI
BR11A/B	WA	BRRI	BR17R	BRRI
Local germplasm	**Source**			
Luhagara, Malail, Binnimuri, Sharisha Mota, Dongra, Kajalsail, Kacha Nonia, Khato Vajan, Sonaroti, Jupri	Germplasm bank, BRRI			

Table 2. Performance of seven promising hybrids at five BRRI research stations during T. aman 2010.[a]

Designation	Days to maturity (av.)	Plant height (av.)	Yield (t/ha)					
			GAZ	COM	KUS	RAJ	RAN	Av.
BR9A/BR12R	107.4	111.4	2.98	1.48	2.91	2.90	4.30	2.91
BR9A/BR15R	107.8	111.7	3.03	1.15	3.44	2.56	4.46	2.93
BR10A/BR12R	111.8	109.7	3.49	1.16	3.81	4.24	4.44	3.43
BR10A/BR15R	112.0	91.7	3.61	1.75	4.31	4.34	4.74	3.75
II32A/BR10R	112.0	109.3	2.46	1.18	4.09	4.97	4.47	3.43
II32A/BR12R	112.4	108.2	3.38	1.13	4.13	4.51	5.06	3.64
II32A/BR15R	112.6	110.1	5.20	1.94	4.88	5.33	4.99	4.47
BRRI dhan33	112.0	108.6	4.00	2.29	4.02	4.08	4.09	3.70
BRRI dhan39	126.6	102.8	4.74	4.34	3.74	4.71	4.20	4.35

[a]GAZ = Gazipur, COM = Comilla, KUS = Kustia, RAJ = Rajshahi, RAN = Rangpur.

Table 3. Performance of six promising hybrids at four BRRI research stations during boro 2010-11.[a]

Designation	Days to maturity (av.)	Plant height (av.)	Yield (t/ha)				
			GAZ	COM	RAN	BAR	Av.
BR10A/BR12R	155	103.3	6.19	9.0	7.09	8.40	7.67
BR10A/BR15R	155	105.1	6.76	8.1	7.30	9.07	7.81
II32A/BR10R	153	103.5	7.78	8.8	6.95	9.69	8.31
II32A/BR12R	152	101.9	6.60	9.2	7.30	8.73	7.96
BR9A/BR12R	148	102.3	6.32	7.6	6.25	8.17	7.09
BR1A/BR11R	148	96.7	6.61	7.9	5.97	8.00	7.12
BRRI dhan28	143	101.1	6.44	8.3	4.71	6.51	6.49
BRRI dhan29	160	101.9	7.60	9.6	6.91	8.55	8.17
BRRI hybrid dhan2	153	105.1	7.29	9.2	7.07	8.63	8.05
BRRI hybrid dhan3	152	107.2	7.56	10.0	7.71	10.15	8.86

[a]GAZ = Gazipur, COM = Comilla, RAN = Rangpur, BAR = Barisal.

and booting stage, respectively. The rest of the 1/3 MP was applied with a second topdress of urea. Intercultural operations, roguing, GA3 application, and supplementary pollination were performed. Seed yield was 65 kg/plot (1.4 t/ha), 50 kg/plot (1.5 t/ha), and 25 kg/plot (1.2 t/ha) from BR10A, BR11A, and IR58025A, respectively (Table 4).

Similarly, we made an attempt to produce a sufficient quantity of pure CMS seeds during the boro season of 2010-11 for released hybrids. Seed yields of 550 kg (2.20 t/ha), 1,500 kg (2.5 t/ha), and 276 kg (1.8 t/ha) were obtained from BR10A/B, BR11A/B, and IR58025A/B, respectively (Table 5).

Table 4. CMS multiplication of released hybrids during T. aman 2010.[a]

Combinations	Plant height (cm)		50% flowering (days)		PER (%)	OCR (%)	Yield	
							(kg/plot)	(t/ha)
	A line	B line	A line	B line	A line	A line		
BR 10A/B	84	86	73	72	74	34	65	1.4
BR 11A/B	82	85	75	73	77	36	50	1.5
IR58025A/B	88	90	90	79	71	31	25	1.2

[a]PER = panicle exsertion rate, OCR = outcrossing rate.

Table 5. CMS multiplication of released hybrids during boro 2010-11.[a]

Combinations	Plant height (cm)		50% flowering (days)		PER (%)	OCR (%)	Yield		Location
							(kg/plot)	(kg/ha)	
	A line	B line	A line	B line	A line	A line			
BR10 A/B	80	83	121	120	87	45	550	2,200	Gazipur
BR11A/B	82	84	123	121	88	49	1,500	2,500	
IR58025A/B	79	78	120	120	82	43	276	1,800	

[a]PER = panicle exsertion rate, OCR = outcrossing rate.

F_1 seed production of released hybrids

We made an attempt to produce a sufficient quantity of F_1 seeds for subsequent use during the boro season of 2010-11. Parental lines of each hybrid were sown maintaining their actual intervals between A and R lines in a two- or three-staggered system. Thirty-day-old seedlings were transplanted at a spacing of 15 cm × 15 cm with a ratio 2:12 of A and R lines. Fertilizers at 270:130:120:70:10 kg/ha urea, TSP, MP, gypsum, and zinc were applied. Intercultural operations, irrigation, roguing, GA3 application, and supplementary pollination were performed as per need. Seed yields were 15 kg (1.50 t/ha), 500 kg (2.45 t/ha), 420 kg (2.85 t/ha), and 37 kg (1.80 t/ha) from IR58025A/BR827R, BR10A/BR10R, BR11A/BR15R, and IR58025A/BR10R, respectively (Table 6).

Dissemination of hybrid rice technology

To expand and popularize BRRI-developed hybrid rice varieties, we took some initiative to encourage seed companies to produce hybrid rice seed domestically by supplying them with parental line seed free of cost. In this connection, in the last reporting year, we supplied 1,387.5 kg of parental line and F_1 seeds to 21 seed companies and BADC (Table 7).

Table 6. F_1 seed production of BRRI hybrid dhan1, BRRI hybrid dhan2, BRRI hybrid dhan3, and BRRI hybrid dhan4 during boro 2010-11.[a]

Combinations	Plant height (cm)		50% flowering (days)		PER (%)	OCR (%)	Plot size (m^2)	Yield (kg/ plot)	Yield (kg/ ha)	Location
	A	R	A	R	A	A		F_1 seed		
BRRI hybrid dhan1	76	105	123	133	84	36	100	15	1,500	Rangpur
BRRI hybrid dhan2	79	90	122	122	88	46	2,040	500	2,450	Habigonj
BRRI hybrid dhan3	81	89	123	124	87	48	1,474	420	2,850	Comilla
BRRI hybrid dhan4	80	89	120	121	85	41	205	37	1,800	Gazipur

[a]PER = panicle exsertion rate, OCR = outcrossing rate.

Table 7. Amount of parental line and hybrid seed supplied to different organizations.

Recipient	No.	F_1 (kg)	A line (kg)	B line (kg)	R line (kg)
BADC	1	0.0	150.0	–	30.0
Seed companies	21	75.0	706.0	–	150.0
Farmers	65	130.0	1.0	–	0.5
BRRI R/S	4	–	102.0	9.0	34.0
Total	91	205.0	959.0	9.0	214.5
Grand Total		1,387.5			

Future action plans

The government of Bangladesh has taken pragmatic steps to develop and use hybrid rice technology on a large scale by involving public, private, and nongovernment organizations. Research, seed production, and technology transfer agencies in the public, private, and NGO sectors are also interested in exploring the prospects of this technology. The government has allowed some NGOs and private seed companies to introduce and commercialize exotic hybrids for large-scale cultivation by farmers with a view to obtaining immediate benefit from this technology. Special attention has been given to developing hybrid rice varieties within the country and, in this regard, a hybrid rice component under a revenue budget has been formed in BRRI. The foremost constraint to overcome by researchers is to identify heterotic hybrid combinations that are adaptable under Bangladeshi conditions and able to outyield the most popular commercial varieties by at least 20%. Another hurdle to be overcome is to develop a cheaper seed production package, which is necessary to make this technology commercially viable by creating job opportunities for rural people. Zoning of hybrid rice seed production is urgently needed such as a seed village where only one variety will be produced without any barrier. The search for cytoplasmic diversity is also very necessary for avoiding sudden disease infestation.

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Notes

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Progress in rice breeding and production in China

Cao Liyong, Yu Ping, Zhan Xiaodeng, and Cheng Shihua

In this country report, we summarized the rice production situation, progress in rice functional genomics research, rice breeding, and production achievements in 2011. In addition, we proposed the main problems in rice production, development targets, and future challenges.

Keywords: rice breeding, rice production

Rice is a major component of the diet of more than half of the world's population. Rice has less than 30% of the grain crop area and nearly 40% of grain production in China.

In 2011, grain production achieved the eighth successive annual increase, with five consecutive years of steady production of more than 500 million tons. Total production of 550 million tons set a new record, which achieved the grain capacity planning level for 2020, and played an important role in maintaining the economy and helping society to develop steadily. According to the state statistical bulletin, the total crop area was 110.57 million ha, 696,000 ha higher than in 2010; total production was 571.21 million tons, increasing by 24.73 million tons and 4.5% compared with 2010. In 2011, government institutions at various levels actively carried out a steady increase in grain production activities, governments showed enthusiasm for production, and farmers were motivated. Total rice area was 30.00 million ha, 186,700 ha higher than in 2010; total production was 200.78 million tons, increasing 5.25 million tons, achieving the eighth successive annual increase. Average rice yield was 6.69 t/ha, increasing 0.009 t compared with 2010 (Table 1).

Progress in rice functional genomics research

Gene cloning and transformation are priority research areas of rice biotechnology in China. Many functional genes controlling important agronomic traits such as yield, resistance, quality, and plant type have been cloned by scientists (Tables 2–4). Those genes will be very helpful to battle biotic and abiotic stresses in rice cultivation, for quality improvement, as well as to increase yield.

Table 1. Brief summary of the country and rice situation.

Year	2011
Country population (million)	1,370.50
Population growth rate (%)	0.64
Rural population (%)	50.32
Number of rice farmers	Not available
Total crop area (000 ha)	110,570
Total rice area (000 ha)	30,000
Average rice yield (t/ha)	6.69
Rice production (million t)	200.78
Rice imports (000 t)	578
Rice exports (000 t)	490
Number of government researchers working on rice	Not available
Number of government extension workers	Not available

Table 2. Cloned genes related to plant type, 2011.

Gene	Chr.	Traits	Reference
OsPH1	1	Dwarf	Kovi et al (2011)
DEP3	6	Grain number of panicle, panicle shape	Qiao et al (2011)
OsPIN2	6	Plant height, tiller number, tiller angle	Chen et al (2011)
BC12/GDD1	9	Dwarf	Li J et al (2011)
LB4D	11	Plant height, tiller number	Liang et al (2011)
OsCD1	12	Short panicle, narrow leaf	Luan et al (2011)
HTD3	12	Plant height, tiller number	Zhang et al (2011)

Table 3. Cloned genes associated with yield traits, 2011.

Gene	Chr.	Traits	Reference
GW8	8	Grain size, grain shape	Wang et al (2012)
GS5	5	Thousand-grain weight, grain size, fruiting rate	Li YB et al (2011)
LP	2	Panicle length, panicle shape	Li M et al (2011)
Ghd8	8	Heading date, grain yield	Yan et al (2011)

Table 4. Cloned/mapped genes associated with resistance, 2011.

Gene	Chr.	Traits	Reference
C3H12	1	Bacterial blight resistance	Deng et al (2012)
OsCOI1	1	Cnaphalocrocis medinalis resistance	Ye et al (2012)
OsbZIP16	2	Drought resistance	Chen H et al (2012)
pi55(t)	8	Blast resistance	He et al (2012)
xa34(t)	1	Bacterial blight resistance	Chen et al (2011)
Bphi008a	6	Brown planthopper resistance	Hu et al (2011)
NLS1	11	Bacterial disease resistance	Tang et al (2011)
Pi-47	11	Blast resistance	Huang et al (2011)

In plant type, some genes related to rice dwarf, grain number per panicle, panicle shape, tillering number, and tillering angle (*OsPH1, BC12/GDD1, DEP3, OsPIN2, LB4D, OsCD1, HTD3*) were cloned and studied by Chinese researchers and research results were published by Li J et al (2011), Luan et al (2011), Kovi et al (2011), Qiao et al (2011), and Zhang et al (2011). For yield-related traits, genes controlling grain shape (*GW8*), grain weight (*GS5*), panicle length (*LP*), and heading date (*Ghd8*) were cloned and research results were published by Li YB et al (2011). Li M et al (2011), and Yan et al (2011). For biotic/abiotic stress resistance, genes were cloned for bacterial blight resistance (*C3H12*), *Cnaphalocrocis medinalis* resistance (*OsCOI1*), drought resistance (*OsbZIP16*), *and* brown planthopper resistance (*Bphi008a*). In addition, blast resistance genes *Pi-47 and pi55(t) and* bacterial blight resistance gene *xa34(t)* were mapped. The results were published by Deng et al (2012), Hu et al (2011), Tang et al (2011), Huang et al (2011), and Chen et al (2011).

Plant type

Li J et al (2011) described a rice mutant, *gibberellin-deficient dwarf1* (*gdd1*), which has a phenotype of greatly reduced length of roots, stems, spikes, and seeds. *GDD1* was cloned by a map-based approach, was expressed constitutively, and was found to encode the kinesin-like protein BRITTLE CULM12 (BC12). Microtubule cosedimentation assays revealed that BC12/GDD1 bound to microtubules in an ATP-dependent manner. In addition, GDD1 was shown to have transactivation activity. Therefore, BC12/GDD1, a kinesin-like protein with transcription regulation activity, mediates cell elongation by regulating the GA biosynthesis pathway in rice.

Luan et al (2011) described a curled leaf and dwarf mutant in rice, *cd1*, which exhibits multiple phenotypic traits such a reduction in plant height and leaf width, curled leaf morphology, and a decrease in the number of grains and in panicle length. Map-based cloning indicates that a member of the cellulose synthase-like D (*CSLD*) group is a candidate for *OsCD1*. Analysis of *OsCD1* promoter with GUS fusion expression shows that *OsCD1* exhibits higher expression in young meristem tissues such as fresh roots, young panicles, and stem apical meristem.

Yield-related traits

Wang et al (2012) cloned a quantitative trait locus, *GW8*, which encodes a protein that is a positive regulator of cell proliferation. Higher expression of this gene promotes cell division and grain filling, with positive consequences for grain width and yield in rice. The correlation between grain size and allelic variation at the *GW8* locus suggests that mutations within the promoter region were likely selected in rice breeding programs.

A QTL (*GS5*) in rice controlling grain size by regulating grain width, filling, and weight was cloned (Li YB et al 2011). *GS5* encodes a putative serine carboxypeptidase and functions as a positive regulator of grain size, such that higher expression of *GS5* is correlated with larger grain size. Sequencing of the promoter region in 51 rice accessions identified 3 haplotypes that seem to be associated with grain width. The results suggest that natural variation in *GS5* contributes to grain size diversity and may be useful in improving yield in rice and, potentially, other crops.

Research on biotic and abiotic stress resistance

Deng et al (2012) reported that one of the rice CCCH-type zinc-finger proteins (C3H12) was involved in rice *Xanthomonas oryzae* pv. *oryzae* (*Xoo*). interaction. Activation of *C3H12* partially enhanced resistance to *Xoo*, accompanied by the accumulation of jasmonic acid (JA) and induced the expression of JA signaling genes in rice. The C3H12 protein was localized in the nucleus and possessed nucleic acid-binding activity in vitro. The results suggest that C3H12 positively and quantitatively regulates rice resistance to *Xoo* and that its function is likely associated with the JA-dependent pathway.

Another research group identified a new bacterial blight recessive resistance gene (*xa34(t)*) from the descendant of somatic hybridization between aus rice cultivar BG1222 and susceptible cultivar IR24, which was defined to a 204-kb interval flanked by markers RM10929 and BGID25 on chromosome 1 (Chen et al 2011).

Rice breeding and production

In 2011, 382 new rice varieties were released provincially or nationally that possessed high yield potential and good quality in provincial or national-regional trials and production demonstration tests. A number of new hybrid combinations with outstanding yield and disease resistance were bred. A lot of hybrid rice parents with different advantages and characteristics were created by hybrid breeding and molecular breeding methods. The breeding and extension of new varieties strongly support rice production. Rice-growing area was about 30.00 million ha, average yields reached 6.69 t/ha, and total output attained 200.78 million tons. Both the average yield and total output reached a record high and marked eight years of continuous increases in crop production.

Breeding methods used

Conventional breeding

- Hybridization and selection
- Elite × elite
- Wide hybridization
- Interspecific-subspecific crosses

Molecular breeding

- Marker-assisted recurrent selection for yield
- Marker-assisted pyramiding of disease resistance genes
- Marker-assisted backcrossing

Germplasm enhancement

- Mutation breeding
- Anther culture
- Genetic engineering

Rice breeding progress

Release of new rice varieties. In 2011, with efforts of rice breeders in China, more than 353 rice varieties were released at the provincial level and 29 varieties were released nationally (Fig. 1). Among the 29 new national varieties, there were 3 inbred japonicas, 18 three-line indicas, 1 japonica hybrid, 6 two-line indica hybrids, and 1 indica inbred. Encouraged by favorable policy, more and more seed companies invested in rice breeding. In 2011, 15 national released varieties were developed by public institutes, 8 by seed companies, and 6 through cooperation of public research institutes and seed companies. This indicated that the private sector will invest more in rice breeding in the future.

Super rice breeding. To meet future demand for rice production, a national program on super rice breeding began in China in 1996. This program mainly focused on super hybrid rice breeding. The strategy of super rice breeding was to integrate the use of heterosis and construct an ideal plant type. To increase the genetic diversity of parents, researchers in China applied parents with intermediate subspecies differentiation to increase F_1 yield, selected DNA markers for subspecies differentiation, and developed medium-type restorer lines in subspecies differentiation. It is very important to use germplasm and gene-by-gene introgression of indica and japonica, pyramid and use yield QTLs in cultivated rice, explore and use genes related to high yield and resistance to pests, and with good plant and root architecture in super hybrid breeding programs. Up to 2011, the Ministry of Agriculture had identified 83 varieties as super rice, planted on 6.6 million ha with average yield reaching 9.0 t/ha; among them, 52 varieties were hybrid.

In 2011, the yield of super hybrid rice Y Liangyou 2 reached 13.9 t/ha on a 6.6-ha demonstration area in Hunan Province; it achieved the yield target of third-phase super rice for the first time.

Two-line hybrid rice breeding. In recent years, more and more two-line hybrid rice varieties have been released; in 2011, there were 6 and 51 two-line hybrid combinations

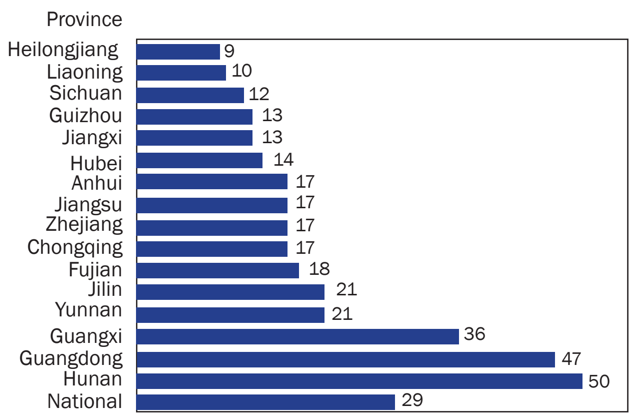

Fig. 1. Number of rice varieties released nationally and provincially in 2011.

released nationally and provincially, respectively (Fig. 2). In 2011, the planting area of two-line hybrid rice reached 2.7 million ha, about 9.0% of the total rice cultivation area and 18.6% of the hybrid rice planting area. In 2010, the top three hybrid varieties with the highest extension area were all two-line combinations. In 2002, a two-line hybrid rice (Liangyou Peijiu) took first place in planting area instead of Shanyou 63, for more than ten years the leading three-line hybrid rice. The cultivation area of two-line hybrid rice will expand with the progress of research on seed production.

Japonica hybrid rice breeding. Outstanding progress has been achieved in japonica hybrid rice breeding. The planting area of the japonica hybrid rice accounted for 0.3 million ha, about 3% of the total japonica rice. One and eight japonica hybrid rice varieties were released nationally and provincially, respectively. Among those, Yongyou series varieties made remarkable achievements. Their extension area reached 154,700 ha, accounting for more than half of the total area of japonica hybrid rice. Especially, the extension area of a single variety (Yongyou 9) surpassed 66,700 ha for the first time. In 2011, the average yield of Yongyou 12 exceeded 13.65 t/ha on a 6.6-ha demonstration area, and the highest yield reached 14.15 t/ha, creating a record high yield in Zhejiang Province.

Elite hybrid rice varieties in China. Elite hybrid rice varieties are Guodao 6, Y Liangyou 1, Xin Liangyou 6, and Zhongzhe You 1 (Table 5).

Prospects and challenges

Main problems in rice production

Farmers' level

- Lack of high-yielding varieties with good quality and multiple resistance
- Lack of market information and low marketing capacity
- Small cultivation scale with low efficiency
- Low profit from rice cultivation

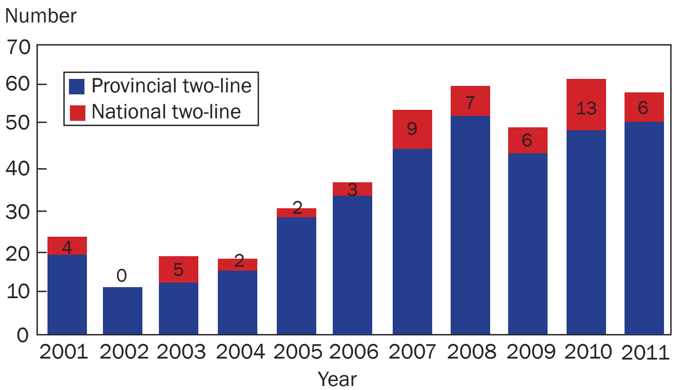

Fig. 2. Two-line hybrid rice varieties released in China (2001-11).

Table 5. Traits of elite hybrid rice varieties.

Variety	Release year	Elite traits	Yield potential (t/ha)	Planting area (ha)
Guodao 6	2007	High yield, good quality	12.5	95,000
Y Liangyou 1	2006	High yield, good quality, wide adaptability	12.5	353,000
Xin Liangyou 6	2005	Good quality, high yield	12.5	271,000
Zhongzhe You 1	2004	High yield, good quality, ideotype	12.3	245,000

National level

- Water shortage and environmental pollution
- How to increase productivity of rice to ensure national food security under decreasing field area?

Future development priorities

Targets

- National food security
- Increasing farmers' income
- Environmental protection

How can this be done? The probable routes include breeding of rice varieties with high yield, good quality, and multiple resistance; technology transfer to narrow the gap between actual and potential yield; low-cost and labor-saving rice cultivation technology; and managing natural resources and using chemicals efficiently.

Challenges

Great achievements have been made, but the following challenges remain:

- How to get sustainable improvement of yield potential, grain quality, and tolerance of biotic and abiotic stresses together?
- Many important genes have been cloned in rice. How can they be used?
- How to combine national food security and farmers' needs?

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Notes

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Hybrid rice research and development in India

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The hybrid rice program in India was launched in 1989 through a systematic, goal-oriented, and time-bound network project with financial support from the Indian Council of Agricultural Research (ICAR), technical backstopping from the International Rice Research Institute, Philippines, and FAO, Rome. Additional support from the UNDP, ICAR, NATP, and Barwale Foundation was the major factor contributing to the remarkable success of hybrid rice technology in the country. So far, 59 hybrids have been released for commercial cultivation and all the hybrids released in the country are based on the three-line breeding system. The area planted to hybrid rice in the country during the wet season (kharif 2011) was around 2 million ha (4.5% of the total rice area of 44 million ha). It is mainly cultivated in the eastern Indian states of Uttar Pradesh, Jharkhand, Chhattisgarh, and Bihar and has contributed 2.5–3 million t of additional rice to India's total rice production.

Considerable success has been achieved in the development of indigenous parental lines (both female and male parents) with good floral traits. An array of hybrids with good grain quality (both unique Basmati type and medium slender [MS] grain type) are developed and made available to the farming community for commercial cultivation. Breeding efforts are intensified to insulate parental lines with resistance to major biotic and abiotic stresses by pedigree, backcross, and genetic male sterility-facilitated population improvement methods.

It is estimated that every year 25,000-30,000 t of hybrid rice seed are being produced in the country and 95% of this by private seed companies. Seed production technology has been perfected over the years and many progressive farmers record more than 3 t of hybrid seed yield per hectare. Large-scale hybrid seed production and marketing of public-bred hybrids are being facilitated through public-private partnership based on a memorandum of understanding (MoU) signed between research institutes and private companies.

Aggressive transfer of technology efforts through compact block frontline demonstrations sponsored by the Department of Agriculture and Cooperation (DAC) resulted in large-scale adoption and popularization of the technology. Ample scope exists to bring more area under hybrid rice in the coming years.

Hybrid rice is a proven and successful technology for rice production, having contributed significantly toward raising rice productivity, improving food security (and thereby farmers' income), and providing more employment opportunities over the past three decades in China. The hybrid rice program in India was launched in 1989 through a systematic, goal-oriented, and time-bound network project with financial assistance from the Indian Council of Agricultural Research (ICAR). Technical support from the International Rice Research Institute (IRRI), Philippines, and FAO, Rome, and additional financial support from the UNDP, ICAR, NATP, and Barwale Foundation were the major factors contributing to the remarkable success of hybrid rice technology in India.

Hybrids released

A strong time-tested three-tier system for evaluation has been put in place. In this system, only hybrids are tested in the Initial Hybrid Rice Trials (IHRTs), whereas, in the next two Advanced Varietal Trials (AVTs), the best hybrid entries are evaluated along with best inbred entries in the same trial. As a result of concerted efforts for more than two decades, a total of 59 hybrids have been released for commercial cultivation in the country. Among these, 31 have been released from the public sector while the remaining 28 have been developed and released by the private sector (Table 1). Out of 59 hybrids, 24 have been released by the State Variety Release Committees, while 35 hybrids have been released by the Central Varietal Release Committee. Among the central releases, seven hybrids (KRH-2, Pusa RH-10, DRRH-2, Sahyadri-4, DRRH-3, Rajlaxmi, and CRHR-32) are from the public sector and the remaining 28 are from the private sector. Table 2 contains the state-wise list of hybrids released in the country. Though 59 hybrids have been released so far, some of them are outdated and some are not in the seed production chain. Table 3 lists the hybrids that are in the seed production chain and available for commercial cultivation. In addition, 30–40 hybrids are being marketed as truthfully labeled seeds by many private seed companies.

Multilocation evaluation of released hybrids

To make a comparative evaluation of hybrids released in the country and to get information on their adaptability in different states across the country, multilocation evaluation of the released hybrids was taken up in three phases. In the first phase, all the hybrids released prior to 1999 were extensively tested during three seasons: kharif 1999 (64 locations), rabi 1999-2000 (15 locations), and kharif 2000 (46 locations). Based on the overall mean (125 locations) pooled over 3 years, the hybrids KRH-2, PHB-71, Sahyadri, PA 6201, NSD-2, and DRRH-1 were found promising and widely adapted. KRH-2 was the top in both kharif seasons, whereas Sahyadri found to be better during the rabi season (Table 4).

In the second phase, all the hybrids released after 2000 were tested in 32–35 locations across the country during kharif 2006 (34 locations), kharif 2007 (35 locations), and kharif 2008 (32 locations) seasons. Based on the criteria of a 10% yield advantage over the best varietal check and 5% over the best hybrid check, promising hybrids for different states have been identified (Table 5).

Table 1. List of hybrids released in India (1994-2012).[a]

Hybrid	Days to 50% flowering	Year of release	Notification no.	Date of notification	Developed by	Released for the states of
APHR-1	100	1994	662(E)	17.IX.1997	APRRI, Maruteru (ANGRAU), Hyderabad	Andhra Pradesh Andhra Pradesh
APHR-2	90	1994	662(E)	17.IX.1997	APRRI, Maruteru (ANGRAU), Hyderabad	Tamil Nadu Karnataka
MGR-1 (CORH-1)	85	1994	360(E)	1.V.1997	TNAU, Coimbatore	
KRH-1	95	1994	1(E)	1.I.1996	ZARS, VC Farm, Mandya (UAS, Bengaluru) RRS,	West Bengal Andhra Pradesh
CNRH-3	95	1995	–		Chinsurah, West Bengal	Pondicherry, Bihar, Karnataka, TN, Tripura, Maharashtra, Haryana, Odisha,
DRRH-1	100	1996	401(E)	15.V.1998	DRR, Hyderabad	Uttaranchal, Rajasthan, and West Bengal
KRH-2	100	1996	401(E)	15.V.1998	ZARS, VC Farm, Mandya (UAS, Bengaluru)	
Pant Sankar Dhan-1	90	1997	425(E)	8.VI.1999	GBPUA&T, Pantnagar	Uttar Pradesh
PHB 71	100	1997	647(E)	9.VI.1997	Pioneer Overseas Corp., Hyderabad	Haryana, UP, TN, AP Karnataka
CORH-2	95	1999	425(E)	8.VI.1999	TNAU, Coimbatore	Tamil Nadu
ADTRH-1	85	1999	425(E)	8.VI.1999	TNRRI, Aduthurai (TNAU)	Tamil Nadu
Sahyadri	100	1998	821(E)	13.IX.2000	RARS, Karjat (BSKKV)	Maharashtra
Narendra Sankar Dhan-2	98	1998	425(E)	8.VI.1999	NDUA&T, Faizabad	Uttar Pradesh
PA 6201	95	2000	92(E)	19.VI.2000	Bayer Bio-Science, Hyderabad	AP, Karnataka, TN, Bihar, Odisha, Tripura, UP, WB, and MP
PA 6444	105	2001	1134(E)	5.XI.2001	Bayer Bio-Science, Hyderabad	UP, Tripura, Orissa, AP, Karnataka, Maharashtra, and Uttarakhand
Pusa RH-10	95	2001	1134(E)	15.XI.2001	IARI[a], New Delhi	Haryana, Delhi, UP, Uttarakhand.

continued...

Table 1. Continued.

Hybrid	Days to 50% flowering	Year of release	Notification no.	Date of notification	Developed by	Released for the states of
Ganga	100	2001	599 (E)	25.IV.2006	Paras Extra Growth Seeds Ltd., Hyderabad	Uttarakhand, Punjab, Nagaland, Haryana, UP, Odisha, Bihar
RH-204	95	2002	283(E)	12.III.2003	Parry Monsanto Seeds Ltd., Bengaluru	AP, Karnataka, TN, West Haryana, Uttarakhand, and Rajasthan
Suruchi	103	2004	122(E)	2.II.2005	Mahyco Ltd., Aurangabad	Haryana, Andhra Pradesh, Gujarat, Odisha, Chhattisgarh, Karnataka, and Mahrashtra
Pant Sankar Dhan-3	92	2004	599 (E)	25.IV.2006	GBPUA&T, Pantnagar	Uttarakhand
NarendraUsarSankar Dhan-3	105	2005			NDUA&T, Faizabad	Saline and alkaline areas of UP
DRRH-2	86	2005	1566 (E)	5.XI.2005	DRR, Hyderabad	Haryana, Uttaranchal, West Bengal, and Tamil Nadu
Rajlaxmi	98/128(Boro)	2005	1572 (E)	20.IX.2006	CRRI, Cuttack	Odisha and boro areas of Assam
Ajay	98	2005	1572 (E)	20.IX.2006	CRRI, Cuttack	Orissa
Sahyadri-2	85	2005	122 (E)	6.II.2007	RARS, Karjat (BSKKV)	Maharashtra
Sahyadri-3	95	2005	122 (E)	6.II.2007	RARS, Karjat (BSKKV)	Maharashtra
HKRH-1	104	2006	122 (E)	6.II.2007	RARS, Kaul (CCSHAU)	Haryana
JKRH-401	110	2006	122 (E)	6.II.2007	JK Agri Genetics Ltd., Hyderabad	West Bengal, Bihar, Odisha
CORH-3	85	2006	1178 (E)	20.VII.2007	TNAU, Coimbatore	Tamil Nadu
Indira Sona	98	2006	1178 (E)	20.VII.2007	IGKVV, Raipur	Chhattisgarh
JRH-4	87	2007	1178 (E)	20.VII.2007	JNKVV, Jabalpur	Madhya Pradesh
JRH-5	87	2007	1178 (E)	20.VII.2007	JNKVV, Jabalpur	Madhya Pradesh
PA 6129	85	2007	1703 (E)	5.X.2007	Bayer Bio-Science, Hyderabad	Punjab, TN, Pondicherry
GK 5003	88	2008	454 (E)	11.II.2009	Ganga Kaveri Seeds Pvt. Ltd., Hyderabad	Andhra Pradesh and Karnataka
Sahyadri 4	88	2008	454 (E)	11.II.2009	RARS, Karjat (BSKKV)	Maharashtra, UP, Punjab, Haryana, and West Bengal
JRH-8	90	2008	449(E)	11.II.2009	JNKVV, Jabalpur	Madhya Pradesh

continued...

Table 1. Continued.

Hybrid	Days to 50% flowering	Year of release	Notification no.	Date of notification	Developed by	Released for the states of
DRH 775	96	2009	2187 (E)	27.VIII.2009	Metahelix Life Sciences Pvt. Ltd., Hyderabad	Jharkhand, Chhattishgarh, and West Bengal
HRI-157	104	2009	2187 (E)	27.VIII.2009	Bayer Bio-Science, Hyderabad	UP, MP, Bihar, Jharkhand, Tripura, Chhattisgarh, Odisha, Maharashtra, Gujarat, Andhra Pradesh, Karnataka, and Tamil Nadu
PAC 835	102	2009	2187 (E)	27.VIII.2009	Advanta India Ltd., Hyderabad	Odisha and Gujarat
PAC 837	100	2009	2187 (E)	27.VIII.2009	Advanta India Ltd., Hyderabad	Western Gujarat, eastern Chattisgarh, northwestern J&K, Andhra Pradesh, and Karnataka
NK 5251	98	2012			Syngenta India Ltd., Secundrabad	Tamil Nadu, Karnataka, Andra Pradesh, Maharashtra and Gujarat
DRRH 3	101	2009	211(E)	29.I.2009	DRR, Hyderabad	Andhra Pradesh, Odisha, Gujarat, Madhya Pradesh, and Uttar Pradesh
US 312	98	2010	2137(E)	31.VIII.2010	Seed Works International, Hyderabad	Tamil Nadu, Karnataka, Andhra Pradesh, Bihar, Uttar Pradesh, and West Bengal
Indam 200-017	96	2010			Indo American Seeds, Hyderabad	Odisha, Chhattisgarh, Gujarat, Maharashtra, and Andhra Pradesh
CRHR-32	112	2010	456(E)	16.III.2012	CRRI, Cuttack	Late–irrigated/shallow lowlands of Bihar and Gujarat
27P11	100	2011	632(E)	25.III.2011	PHI Seeds Private Ltd., Hyderabad	Karnataka and Maharashtra
VNR 202	100-105	2011	456(E)	16.III.2012	VNR Seeds Pvt Ltd., Raipur	Uttar Pradesh, Uttarakhand, West Bengal, Maharashtra, and Tamil Nadu
VNR 204	90-95	2011	456(E)	16.III.2012	–	Chhattisgarh and Tamil Nadu
TNAU Rice hybrid CO 4	100-105	2011			TNAU Coimbatore	Tamil Nadu

continued...

Table 1. Continued.

Hybrid	Days to 50% flowering	Year of release	Notification no.	Date of notification	Developed by	Released for the states of
Sahyadri-5	110	2012			RARS, Karjat	Maharashtra
US-382	94	2012			Seed Works International Pvt. Ltd., Hyderabad	Tripura, Madhya Pradesh, and Karnataka
27P31	96-100	2012			PHI Seeds Private Limited, Hyderabad	Jharkhand, Madhya Pradesh, Karnataka, and Tamil Nadu
HRI 169	94	2012			Bayer BioScience Pvt. Ltd., Hyderabad	Bihar, Chhattisgarh, Gujarat, Andra Pradesh, Tamil Nadu, Jharkhand
RH 1531	95-100	2012			Devgen Seeds & Crop Technology Pvt. Ltd., Secundarabad	Madhya Pradesh, Uttar Pradesh, Andra Pradesh, and Karnataka
PNPH-24	97	2012			Prabhat Agri Biotech Ltd., Hyderabad	Bihar, West Bengal, and Odisha
25P25	89	2012			PHI Seeds Private Limited, Hyderabad	Uttarakhand, Jharkhand, and Karnataka
27P61	102	2012			PHI Seeds Private Limited, Hyderabad	Chhattisgarh, Gujarat, Andra Pradesh, and Karnataka
JKRH 3333	105-110	2012			JK Agri Genetics Ltd., Hyderabad	West Bengal, Bihar, Chhattisgarh, Gujarat, and Andra Pradesh
NPH-924-1	135-140	2012			Nuziveedu Seeds Pvt. Ltd., Hyderabad	West Bengal and Assam

[a] Hybrids in bold are released by Crop Standards and Notification of Varieties (CSCCS & NV).

Table 2. Hybrids released by state.[a]

State	Hybrids
Andhra Pradesh	**APHR-1, APHR-2, PHB-71, PA-6201, PA-6444, RH-204, Suruchi,** DRRH-1, **GK-5003, PAC 837, US 312, DRRH-3, NK 5251, Indam 200-017, HRI 169, RH 1531, 27P61, JKRH 3333**
Assam	**NPH 924-1**
Bihar	**KRH-2, PA-6201, Ganga, JKRH-401, CRHR-32, HRI 169, PNPH 24, JKRH 3333**
Chhattisgarh	Indira sona, **Suruchi, HRI 157, DRH 775, PAC 837, Indam 200-017, VNR-204, HRI 169, 27P61, JKRH 3333**
Delhi	**Pusa RH 10**
Gujarat	**Suruchi, HRI 157, PAC 835, PAC 837, DRRH-3, NK 5251, Indam 200-017, CRHR-32, HRI 169, 27P61, JKRH 3333**
Goa	**KRH-2**
Haryana	**Pusa RH 10, Ganga,** HKRH-1, **PHB-71, RH-204, Suruchi, DRRH-2, Sahyadri-4**
Karnataka	**KRH-1, KRH-2,PHB-71, PA-6201, PA-6444, RH-204, Suruchi, GK-5003, PAC 837, HRI 157, US 312, NK 5251, 27P11, US 382, 27P31, RH 1531, 25P25, 27P61**
Maharashtra	**KRH-2,PA-6444, Suruchi,** Sahyadri, Sahyadri-2, Sahyadri-3, Sahyadri-4, NK 5251, **Indam 200-017, 27P11, VNR 202,** Sahyadri-5
Madhya Pradesh	**PA-6201,** JRH-4, JRH-5, JRH 8, HRI 157, DRRH-3, **US 382, 27P31, RH 1531**
Odisha	**KRH-2, PA-6201, PA-6444, Ganga,Suruchi,** Rajlaxmi, Ajay, **JKRH-401, PAC 835, DRRH-3, Indam 200-017, PNPH 24**
Punjab	**Pusa RH 10, Ganga, PHB-71, PA 6129, Sahyadri**
Pondicherry	**KRH-2, PA 6129, HRI 157**
Rajasthan	**KRH-2, RH-204**
Tamil Nadu	MGR-1, **KRH-2,** CORH-2, ADTRH-1, **PHB-71, PA-6201, RH-204, DRRH-2,** CORH-3, **PA 6129, US 312, NK 5251, VNR 202, VNR 204,** TNAU Rice hybrid Co 4, **27P31, HRI 169**
Tripura	**KRH-2, PA-6201, PA-6444, US 382**
Uttar Pradesh	**KRH-2,** Pant Sankar Dhan-1, Narendra Sankar Dhan-2, **PHB-71, PA-6201, PA-6444, Pusa RH 10, Ganga,** Narendra Usar Sankar Dhan-3, **Sahyadri-4, HRI 157, US 312, DRRH-3, VNR 202, RH 1531**
Uttarakhand	**PA-6444, Ganga, RH-204,** Pant Sankar Dhan-3, **DRRH-2, VNR 202, 25P25**
West Bengal	**KRH-2,** CNRH-3, **PA-6201, DRRH-2, JKRH-401, Sahyadri-4, DRH 775, US 312, VNR 202, PNPH 24, JKRH 3333, NPH 924-1**
Jharkh	**DRH 775, 27P31, HRI 169, 25P25**
Jammu and Kashmir	**PAC 837**

[a]Hybrids in bold are released by CSCCSN & RV.

Table 3. Hybrids currently available for cultivation.

	Central releases	State releases
Public sector	KRH 2, Pusa RH 10, DRRH 2, Rajlaxmi, Sahyadri 4, DRRH 3, CRHR 32	PSD 3, Ajay, CoRH 3, Indira Sona, JRH 8
Private sector	PHB 71, PA 6129, PA 6201, PA 6444, JKRH 401, Suruchi, GK 5003, DRH 775, HRI-157, PAC 835, PAC 837, US 312, Indam 200-017, NK 5251, 27P11	

Table 4. Hybrids found suitable for other states (other than the one for which they are released) based on MLT data, phase I.

Hybrid	Released for	Found suitable for other states based on MLT performance (1999 and 2000)
DRRH-1	Andhra Pradesh	Tripura
CORH-2	Tamil Nadu	Tripura
Sahyadri	Maharashtra	Tripura
NSD 2	Uttar Pradesh	Tripura and Maharashtra

Table 5. Hybrids found suitable for other states (other than the one for which they are released) based on MLT data, phase II.[a]

Hybrid	Released for	Found suitable for other states based on MLT performance (2006, 2007, and 2008)
Early group		
CORH-3	Tamil Nadu	New Delhi, Uttarakhand, Assam, Chhattisgarh, Madhya Pradesh, Odisha, and West Bengal
DRRH-2	Haryana, Uttarakhand, West Bengal, and Tamil Nadu	New Delhi, Assam, Chhattisgarh, Madhya Pradesh, Odisha, Uttar Pradesh, and Gujarat
Mid-early group		
PSD-3	Uttarakhand	Assam, Madhya Pradesh, West Bengal, Andhra Pradesh, and Tamil Nadu
Medium group		
CRHR-5	Odisha	Bihar and Andhra Pradesh
JKRH-2000	West Bengal, Bihar, and Odisha	Jharkhand
PA 6444	Uttar Pradesh, Tripura, Odisha, Andhra Pradesh, Karnataka, Maharashtra, and Uttarakhand	Jharkhand and Gujarat

[a]States in bold represent hybrids performing well in all three seasons.

In the third phase, the seven hybrids released after 2009 were tested in 26 locations across the country during kharif 2010. Four hybrids (PAC 835, PAC 837, Indam 200-017, and DRH-775) have shown a significant yield advantage over the checks (Table 6).

Evaluation of hybrids under abiotic stress

Hybrids show better tolerance of abiotic stresses and therefore released hybrids were tested under different abiotic stresses such as moisture stress (rainfed upland/aerobic) and saline/alkaline soil conditions to assess their relative performance. Many hybrids were found to be promising under different abiotic stresses (Table 7).

Grain quality improvement

Cooking quality preferences vary from region to region. Rice is a cereal that is consumed mainly as whole milled and boiled grain. Therefore, rice quality has to be considered from the viewpoint of milling quality, grain size, shape, and appearance;

Table 6. Promising hybrids identified in MLT phase III (kharif 2010).[a]

Hybrid	DFF	Yield (kg/ha)				
		Mean	North	East	West	South
Mid-early						
Indam 200-017	96	5,602	5,326	5,312	6,004	5,684
				(20)	(14)	
		[6]	[20]	[5]		[9]
DRH-775	97	5,662	5,382	5,492	5,752	5,832
		(10)		(24)		
		[8]	[22]	[9]		
IR64 (national check)	92	4,843	4,844	4,387	4,968	5,207
Local check	97	5,166	5,830	4,417	5,271	5,670
PA 6201 (hybrid check)	95	5,261	4,427	5,038	5,970	5,198
Medium						
PAC-835	97	5,721	6,311	5,144	6,134	5,892
		(14)	(22)		(18)	(18)
		[10]	[15]		[19]	[9]
PAC-837	97	5,724	6,039	5,194	5,181	6,488
		(14)	(16)			(30)
		[10]	[10]	[6]		[20]
Jaya (national check)	98	5,039	5,189	4,928	5,205	5,006
Local check	97	4,832	5,123	4,455	5,103	4,932
KRH-2 (hybrid check)	96	5,207	5,503	4,898	5,172	5,475

[a] ( ) = yield advantage in percent over the best varietal check.
[ ] = yield advantage in percent over the best hybrid check.

Table 7. Hybrids suitable for abiotic stress conditions.

Abiotic stress	Promising hybrids
Rainfed uplands	PHB-71, KRH-2, CORH-2, PA-6201, JRH-2, PSD-3, DRRH-2, JRH-8
Saline–alkaline soils	CORH-2, KRH-2, DRRH-2, JRH-8, PHB-71, JKRH-2000, JKRH-2004, Indam 300-007
Aerobic	PHB-71, KRH-2, PA 6444, JKRH 3333, DRRH 2, PSD-3, Sahyadri-3, HRI-148

and cooking characteristics. A hybrid should possess a high turnout of whole grain (head) rice and total milled rice, with varying length-/breadth-ratio (L/B) ranging from 2.5 to 3 mm, medium (5.5–6.6 mm) to long slender (> 6.6 mm) translucent grain, and intermediate gelatinization temperature (GT) and amylose content (AC). In addition, high-quality rice such as Basmati should have lengthwise expansion without an increase in girth coupled with a distinct aroma. The recently released hybrids have better quality features (Table 8) and this became possible with the development of appropriate parental lines.

A perusal of the area covered under hybrids indicates that hybrids have not made a dent in the southern region of the country. This is because the people in southern India prefer medium-slender grain, premium-quality rice such as BPT 5204, but a majority of the hybrids have long grains. Now, many hybrids with medium-slender grains and cooking quality traits similar to those of BPT 5204 are available for commercial cultivation. These hybrids have a yield advantage of more than 20% over BPT 5204, with 10–15 days of reduced growth duration (Table 9).

Resistance to insect pests and diseases

The incorporation of resistance to major insect pests and diseases is one of the major objectives of the hybrid rice program. In addition to the development of parental lines with high resistance to biotic stresses, hybrids in the coordinated trials are regularly screened for resistance to major insect pests and diseases through national hybrid rice screening nurseries. Table 10 lists the recently released hybrids with resistance to or tolerance of insect pests and diseases.

Improvement of parental lines

Breeding efforts are intensified to fortify parental lines with resistance to major biotic and abiotic stresses and pedigree, backcross, and genetic male sterility-facilitated population improvement methods are used.

Restorer line improvement

Single, three-way, and multiple crosses among restorers and partial restorers were used to develop a large number of segregating generations. Depending on the purpose, the type of crosses used are $R_1 \times R_2$, $R_1 \times (R_2 \times R_3)$, $R_1 \times PR$, $R_1 \times (PR \times R_2)$, $R_1 \times (PR_1 \times PR_2)$, $PR \times (R_1 \times R_2)$, $PR_1 \times (R_1 \times PR_2)$, $(R_1 \times R_2) \times (R_3 \times R_4)$, $(R_1 \times PR_1) \times (R_2 \times PR_2)$, and so on. The size of the segregating populations ranged from 2,000 to 3,500

Table 8. Grain quality characteristics of recently released hybrids.[a]

Hybrid	Hulling (%)	Milling (%)	HRR (%)	KL (mm)	KB (mm)	L/B ratio	Grain type	KLAC (mm)	ER	WU (mL)	VER	ASV	AC (%)
DRRH 3	80.2	71.7	67.3	5.28	2.00	2.64	MS	–	–	–	–	4.0	23.8
US 312	72.1	70.0	68.0	6.10	2.02	2.95	MS	–	–	–	–	5.0	23.1
Indam 200-017	–	72.3	58.9	6.13	2.27	2.69	LB	–	–	–	–	5.5	24.3
CRHR-32	–	71.0	51.6	5.47	2.09	2.61	MS	–	–	–	–	5.0	25.6
NK 5251	–	72.1	69.1	6.00	1.96	3.06	LS	–	–	–	–	5.0	23.2
27P11	80.3	72.2	62.0	5.22	1.82	2.87	MS	8.5	1.63	275	5.6	5.0	24.3
VNR202	–	72.2	62.0	5.60	2.10	2.60	MS	–	–	–	–	4.5	23.3
VNR204	–	72.7	67.2	6.62	1.98	3.30	LS	–	–	–	–	4.0	24.1
TNAU Rice Hybrid Co4	84.3	68.6	62.5	5.67	1.91	2.96	MS	9.5	1.67	-	5.0	4.0	24.0
Sahyadri-5	–	62.5	–	6.70	2.18	3.07	LS	13.7	1.89	250	2.3	5.5	24.7
US382	–	71.7	63.8	6.10	2.10	2.90	LB	–	–	–	–	4.6	22.5
27P31	–	70.5	62.7	6.41	2.20	2.91	LB	–	–	–	5.5	4.8	21.9
HRI169	–	71.0	63.0	6.53	2.00	3.32	LS	–	–	–	–	5.5	23.0
RH1531		70.8	62.8	–	–	–	LS	–	–	–	–		23.5
PNPH24	78	70.7	62.7	6.23	2.07	3.01		10.2	1.68	280	5.6	5.3	22.5
25P25	79.9	69.1	65.0	6.70	2.01	3.32	LS					7.0	23.8
27P61	81.3	70.3	65.0	5.20	2.00	2.60	MS	8.7	1.67	183	4.6	3.7	25.4
JKRH3333	80.5	72.3	62.2	5.27	2.00	2.60	MS	10.1	1.90	200	5.0	4.3	24.4
NPH924-1	81.0	71.3	63.3	5.54	2.07	2.67	MS	10.4	1.87	200	4.5	5.0	20.8

[a]HRR = head rice recovery, KL = kernel length, KB = kernel breadth, L/B = length/breath, KLAC = kernel length after cooking, ER = elongation ratio, WU = water uptake, VER = volume expansion ratio, ASV = alkali spreading value, AC = amylose content, MS = medium slender, LS = long slender, LB = long bold.

Table 9. Promising hybrids with medium-slender grain quality.[a]

Hybrid	Grain yield		Grain quality traits					
	t/ha	Advantage (%)	Milling (%)	HRR (%)	WU (ml)	ASV	AC (%)	GC (mm)
DRRH-3	6.1	33	72	67	205	5.0	23.8	63
27P11	5.8	26	72	62	275	5.0	22.9	26
TNAU Rice Hybrid Co4	6.5	–	69	62	–	4.0	24.0	65
JKRH 3333	5.9	23	72	62	200	4.3	24.4	44
BPT 5204 (Check)	4.6	–	72	68	200	5.0	23.4	23

[a]HRR = head rice recovery, WU = water uptake, ASV = alkali spreading value, AC = amylose content, GC = gel consistency.

Table 10. Pests and disease reactions of recently released hybrids.

Hybrid	Resistant/moderately resistant[a]
HRI-157	BLB, RTV, BS
PAC 837	BL, RTV, BS, GLH
DRRH-3	BL, RTV, WBPH
US 312	BL, RTV, BS, WBPH, GM
Indam 200-017	BL, BS, SB, LF
CRHR-32	RTV, ShBL
27P11	BL, BLB, ShBL, BS
VNR202	BL, BLB, RTV, ShBL, BS
VNR204	RTV, ShBL, BS, LF
US382	BL, BLB, RTV, ShBL, BS, SB, BPH, WBPH, GM, LF
27P31	BL, BLB, RTV, ShBL, BS
HRI169	BL, RTV, ShBL, BS, SB, BPH, WBPH, GM, LF
RH1531	BL, BS, BPH, WBPH
PNPH21	BL, BLB, GLH, WBPH
25P25	BL, RTV, ShBL, BS
27P61	BL, BS, SB, BPH, WBPH, LF
JKRH3333	BLB, RTV, BS, WBPH
NPH924-1	BL, BLB, ShBL, GLH, BPH, WBPH

[a]BL = blast, BLB = bacterial leaf blight, RTV = rice tungro virus, ShBl = sheath blight, BS = brown spot, GLH = green leafhopper, SB = stem borer, BPH = brown planthopper, WBPH = whitebacked planthopper, GM = gall midge, LF = leaffolder.

plants. As per the objective of the program and the availability of good segregants with desirable traits, single plants were selected and advanced to further generations. In addition to normal visual selection based on phenotype, selection for specific measured traits was taken into consideration, and a wide range of genetic diversity among the selected individuals was maintained. During the period under report, 765 restorers were developed (Table 11). Most of the new restorers possess ideal plant stature and floral traits suitable as good pollinators in commercial hybrid seed production.

A large number of parental lines developed from these programs are regularly used in the development of hybrids. The status of use of the new parental lines is given in Table 12.

Maintainer line improvement

Outstanding partial maintainers with many desirable traits were used in the breeding program. As indicated in restorer line improvement, single, double, and multiple crosses among maintainers and outstanding partial maintainers were used to develop large segregating generations. The population size in F_2 ranged from 1,600 to 2,500 plants and careful selection was exercised for outcrossing and combining ability-related traits by retaining sufficient genetic diversity of the segregants. Selection for plant type, grain type, stigma exsertion, and other easily observable traits was made in the early segregating generations (Table 13). During the period under report, 365 new maintainer lines were developed.

Applying biotechnological tools to improve hybrid rice

Molecular-marker technology is being effectively integrated into the hybrid rice breeding program in the assessment of genetic purity of hybrid seeds and parental lines, identification of fertility restorer genes and their introgression into parental lines,

Table 11. Development of restorers.

Type of crosses	No. of lines developed
R1 × R2	200
R × PR	180
R1 × (R2 × PR)	125
R × (PR1 × PR2)	140
R1 × (R2 × R3)	120
Total	765

Table 12. Status of utilization of new parental lines at DRR, Hyderabad.

Status of use	No. of entries
No. of hybrids released/in advanced stage of release	3
No. of hybrids in national trials	4
No. of hybrids in station trials	50
No. of restorers in experimental hybrid seed production	60
No. of new CMS lines developed	15
No. of B lines in CMS conversion program	20
No. of breeding lines released as varieties	3

Table 13. Development of maintainers.

Type of crosses	No. of lines developed
$B_1 \times B_2$	100
B × PM	75
$B_1 \times (B_2 \times B_3)$	60
$B_1 \times (PM \times B_2)$	70
$B_1 \times (PM_1 \times PM_2)$	20
B_1 × PM//PM	40
Total	365

introgression of biotic-stress resistance genes into hybrid rice parental lines, and the screening of genotypes for the presence of wide compatibility (WC) genes, and these efforts are enhancing hybrid rice breeding efficiency.

Hybrid seed production

For the commercial viability of hybrid rice technology, the development of an efficient and economical seed production package is a prerequisite. The extent of adoption of this innovative technology depends primarily on the magnitude of realizable heterosis at the field level and the availability of pure seed at a reasonable cost. Seed production is the most crucial link between the breeders developing hybrids and the farmers cultivating them. Through extensive trials on different components such as suitable locations, seasons, planting time, planting geometry, row ratios, GA_3 application, and supplementary pollination, etc., a package for the production of hybrid seed was optimized. Using the package developed for hybrid rice seed production, average seed yields obtained in large-scale seed production are 1.5–2.5 t/ha. This is a very lucrative enterprise and many hybrid rice seed growers in Andhra Pradesh have benefited by undertaking this activity. In addition, this generates additional employment of 60–80 person days/ha, particularly for rural women in activities such as leaf clipping, supplementary pollination, roguing, etc.

At present, large-scale seed production (> 90%) is mainly concentrated in a few districts of Andhra Pradesh (Karimnagar, Warangal, and Nizamabad). It is essential to identify alternate areas for seed production as the demand for hybrid rice is increasing and the existing areas of seed production are almost saturated. Efforts are therefore being made to identify suitable locations based on IMD and GIS data. A few promising locations suitable for large-scale seed production have been identified (Table 14).

Private seed companies are producing more than 90% of the hybrid seed in the country. To take advantage of the strong private-sector network in large-scale hybrid seed production and marketing, and to popularize public-sector-bred hybrids, a PPP mode is being actively pursued in India by signing a memorandum of understanding (MOU) with private seed companies to help in spreading hybrid rice technology faster (Table 15). Consequent to these efforts, the area under hybrid rice in the country reached 2.0 million hectares (4.5% of the total rice area) during 2011.

Table 14. Alternate promising areas suitable for large-scale hybrid seed production in the rabi season.

No. of favorable weeks during flowering (February and March)	States (districts)
7–8	AP (Khammam), Karnataka (Haveri, Udupi), North Goa, Tamil Nadu (Dharmapuri, Madurai, Tiruvnnamalai, Vellore, Karur, Pudukottai, Tirunelveli, Tullukudi), Kerala (Trissur)
5–6	Kerala (Malapuram), Odisha (Malkargiri, Baleshwar, Tajapur, Koraput, Naya).

Table 15. Details of MOUs with private seed companies.

Hybrids	Developed by	MOU with no. of companies
DRRH-2 and DRRH-3	DRR, Hyderabad	18
Pusa RH-10	IARI, New Delhi	20
PSD-1 and PSD-3	GBPUAT, Pantnagar	1
CORH–3	TNAU, Coimbatore	1
Ajaya and Rajalakshmi	CRRI, Cuttack	2
KRH-2	UAS, Mandya	1
Sahyadri-1	BSKKV, Karjat	1
JRH-4 and JRH-5	JNKV, Jabalpur	1

Large-scale cultivation of hybrid rice

During 2011, hybrid rice was planted on 2.0 million ha and an additional rice production of 2.5 to 3.0 million t was added through this technology. Uttar Pradesh is the leading state, with more than 0.78 million ha of area, followed by Bihar (0.33 million), Chhattisgarh (0.21 million), and Jharkhand (0.2 million) (Table 16).

Technology transfer

To create awareness about the advantages of taking up hybrid rice cultivation among rice farmers, around 12,000 compact block frontline demonstrations (FLDs) were organized across the country under the macro-management scheme of the Ministry of Agriculture, which is being coordinated and implemented by DRR, Hyderabad. This is an ongoing activity and efforts for technology transfer are being intensified and large numbers of demonstrations are being organized in many more states to popularize the technology. In most of the demonstrations organized, the hybrids have outyielded the best inbred check varieties of the region (Tables 17 and 18).

To impart the knowledge and necessary skills for hybrid rice cultivation and hybrid rice seed production, appropriate training programs (> 500) were organized for farmers, farm women, seed growers, seed production personnel of public and private seed agencies, extension functionaries of State Departments of Agriculture, and of-

Table 16. State-wise area under hybrid rice (kharif 2011).

State	Area in 000 ha	State	Area in 000 ha
Andhra Pradesh	24	Karnataka	7
Northeast	41	Maharashtra	41
Bihar	328	Madhya Pradesh	83
Chhattisgarh	207	Odisha	53
Gujarat	80	Punjab	14
Haryana	99	Tamil Nadu	2
Himachal	2	Uttar Pradesh	782
Jammu and Kashmir	5	Uttarakhand	5
Jharkhand	212	West Bengal	15
	Total		**2,000**

Table 17. Frontline demonstrations organized.

State	Hybrids demonstrated	No. of demonstrations (1 ha each)	Yield advantage (kg/ha)
Uttar Pradesh	NSD-2, PSD-1, PSD-3, PA 6444, PHB-71, KRH-2	2,876	850–2215
Karnataka	KRH-2, DRRH-3	1,903	700–1650
Maharashtra	Sahyadri, KRH-2, PHB-71, PA 6444	1,485	1450–2610
Andhra Pradesh	PHB-71, PA 6444, DRRH-1	600	650–1170
Tamil Nadu	CORH-2, CORH-3, ADTRH-1, PHB-71, DRRH-3	1,069	715–1210
West Bengal	PA 6444, PHB-71, KRH-2, CNRH-3	710	1020–1670
Odisha	PA 6444, PHB-71, KRH-2	858	810–1050
Uttaranchal	PSD-1, PSD-3, PHB-71	640	780–1158
Goa	KRH-2, Sahyadri	680	780–1155
Bihar, Chhattisgarh, Jharkhand, Punjab, Haryana, Gujarat, Tripura	KRH-2, PHB-71, PA 6444, Sahyadri, DRRH-1, PSD-3	1,180	950–1870
	Total	**12,001**	

ficials of SAUs and NGOs, etc. The duration of the training programs varied from 1 to 6 days. In all, 536 training programs were conducted throughout the country and 15,180 participants were trained (Table 19).

Major challenges

Despite having great potential to enhance the production and productivity of rice in the country, hybrid rice has not been adopted on a large scale as was expected because of several constraints. Some of the major constraints follow:

Table 18. Promising hybrids identified in FLDs.

State	2008	2010	2011
Gujarat			DRRH-3
Jharkhand	PA 6444	PA 6444	PA 6444
	PHB 71	PA 6444 (SRI method)	
	Pusa RH 10		
Karnataka	KRH-2		DRRH-3
Tamil Nadu	CORH-3	CORH-3	CORH-3
			DRRH 1
Uttar Pradesh	PHB 71	PHB 71	PA 6444
	PA 6444		PHB 71
			DRRH-3
Chhattisgarh			Indirasona
Madhya Pradesh			PA 6201

Table 19. Training programs organized.

Theme	Duration (days)	Clientele	Number of	
			Training programs	Persons trained
Hybrid rice cultivation	1	Farmers	200	8,060
	1	Farm women	50	1,300
Hybrid rice seed				
Production technology	3	Seed growers	90	1,800
	5	Seed production personnel	106	2,225
Hybrid rice technology	5	Extension workers, officials of state DOA, SAUs, and NGOs	87	1,730
Hybrid rice breeding	6	Breeders from public and private sector	1	18
Winter school on hybrid rice technology	21	Scientists from ICAR, assistant professors from SAUs	2	47
		Total	536	15,180

- Nonavailability of long-duration hybrids suitable for shallow lowlands and coastal areas.
- Nonavailability of strong-culmed, nonlodging, and biotic stress-resistant hybrids for northwestern India.

- Lower acceptability of aroma and sticky hybrids and need for highly specific quality requirements such as medium slender-type hybrids in southern India.
- The moderate (15–20%) yield advantage in hybrids is not economically very attractive and there is a need to further increase the magnitude of heterosis.
- The lower market price offered and discrimination against hybrid rice produce by millers/traders act as a deterrent for many farmers to take up hybrid rice cultivation.
- Higher seed cost is another deterrent for large-scale adoption and hence there is a need to enhance the seed yield in hybrid rice seed production to reduce the seed cost.
- Inadequate efforts for creating awareness and for technology transfer.
- The involvement of public-sector seed corporations in large-scale hybrid rice seed production has been minimal.
- Nonavailability of hybrids for the boro season whereas there is good scope to grow rice hybrids for higher yields.
- The lack of funding support for public-sector research on hybrid rice in recent years is also one of the reasons for the slower progress in hybrid rice research.

Most of these constraints are being addressed with the right earnestness through the ongoing research projects and through aggressive transfer of technology efforts and by strengthening public-private partnership.

Future outlook

Tremendous efforts have been made by all concerned to usher in an era of hybrid rice in the country. The development of heterotic hybrids by researchers, large-scale production of hybrid seed by various seed agencies, and transfer of this technology to end-users by extension agencies must go hand in hand for this technology to have a real impact in Indian agriculture. Though this technology has been introduced to Indian agriculture, the successful large-scale adoption of this innovative technology in the future primarily depends upon its economic attractiveness. Rice hybrids with a still higher magnitude of heterosis coupled with better grain, cooking, and eating quality and possessing resistance to major pests and diseases have to be developed.

Seed production technology has to be further refined to obtain average seed yields of 2.5 to 3.0 t/ha on a large scale, so that the cost of hybrid rice seed can be reduced to Rs. 100/kg. Top priority has to be given to maintaining the purity of parental lines and producing high-quality hybrid seed. Involvement of seed agencies in the public sector, NGOs and farmers' cooperatives along with the private seed sector, which is already doing its best, will be crucial for meeting the increased demand for hybrid seed in the years to come.

Biotechnological tools have to be deployed wherever necessary to enhance breeding efficiency and to save time. The transfer of hybrid rice technology from research farms to farmers' fields is as important as developing the hybrids. Extension agencies have to play a greater role in creating much-needed awareness among farmers about the advantages of cultivating hybrid rice through various innovative approaches.

Policy decisions on providing a subsidy to meet the higher seed cost and giving a minimum support price for rice hybrids for the next 4–5 years would be very helpful for bringing more area under hybrid rice. Despite the few minor problems faced in the initial stages, timely and favorable decisions by policymakers and the active involvement of researchers, seed producers, and extension workers would certainly lead to successful hybrid rice cultivation on a large scale in India during the coming decades. The government of India is also emphasizing the adoption of hybrid rice in its prestigious program on "Bringing Green Revolution to Eastern India," which is now being implemented. Hybrid rice technology is likely to play a major role in increasing rice production in the country, thereby contributing significantly to national food security.

Notes

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Hybrid rice adoption in Indonesia: successes and challenges

Satoto and Made J. Mejaya

Adoption of hybrid rice in Indonesia has been increasing gradually since 2005. Seventy-one hybrid rice varieties were released up to 2012. At the farmer level, local hybrid Hipa11 yielded 9.93 t/ha and Hipa8 yielded 9.55 t/ha, which was higher than the yield of inbred variety Inpari13 (8.62 t/ha). In other farmers' fields, Hipa11 yielded 9.21 and 10.87 t/ha and Hipa8 9.36 and 8.11 t/ha, which was higher than the yield of the most popular inbreds in that location, such as Logawa that yielded 7.83 t/ha. The total area of hybrid rice cultivation was about 650,000 ha in 2012 and this is expected to increase to about 1,500,000 ha soon. On the commercial scale, seed yield still varies, with an average of 1.2 t/ha. There are some challenges to hybrid rice dissemination, such as unstable hybrid performance due to varied cultivation management, poor resistance to pests and diseases, inadequate seed quality, unstable seed yield, and a very high cost of production. In general, the following points could be made: seed production techniques are being developed even though they have not reached their optimum level yet. This is most likely due to crop susceptibility to major pests and diseases, unreasonably high expectations of farmers regarding hybrid rice yield, inappropriate cultivation techniques, unsuitable planting area, seed impurity of parental lines, unstable seed yield, expensive seed prices, and the habit of some farmers to save their paddy grain from the first crop for seed for the next planting season.

Keywords: hybrid rice, adoption, Indonesia

The average yield of rice in Indonesia in 2011 was 5.1 t/ha, with a total production of 65.39 million tons (BPS 2011).This yield actually decreased 1.63% from the 2010 production. The yield decrease was estimated to be about 0.22% caused by a decrease in harvested area, and 1.42% caused by less productivity. Boosting rice production while conserving the environment to secure sustainable food availability is a high priority in Indonesia as a consequence of the increasing population and diminished agricultural resources, mainly land and water. Hybrid rice would be among the options to achieve this goal. In order to achieve the target of increasing rice production by 5%

per year during 2011-14 and obtaining a surplus of 10 million tons of milled rice in 2014 (Directorate General for Food Crops 2012), the development of high-yielding rice varieties was considered as a strategic program. Hybrid rice technology has been selected as an option in the integrated efforts to increase national rice production in Indonesia. There are four technical reasons for developing hybrid rice technology in Indonesia: (1) the yield leveling-off of modern inbred varieties, (2) Indonesia has potential as a tropical country to develop hybrid rice, (3) the good possibility of developing indica × javanica hybrids, and (4) a good opportunity to develop hybrid rice for specific tropical adaptation (Satoto et al 2006).

Research on hybrid rice in Indonesia began in 1983 with the evaluation of hybrids and introduced breeding materials as the major activities. The success of the commercial use of hybrid rice technology in India, Vietnam, and the Philippines has encouraged the government of Indonesia to intensify the research and development of hybrid rice in the country since 1999. Activities were not only evaluating materials from IRRI but also developing hybrid rice by using local genetic materials. The main target was to obtain hybrid rice that was more adaptive to the Indonesian environment and yielded about 20% higher than the existing rice varieties. More intensive activities involving various disciplines have been carried out since 2001, with the main target of increasing heterosis, providing cultural technologies suitable for particular hybrid rice varieties, and developing technology packages for hybrid rice seed production. Overall activities from 2000 to 2005 were reported at the International Rice Conference in September 2005 in Bali, Indonesia (Satoto et al 2006), and, for 2005-08,at the 6th International Symposium on Hybrid Rice in September 2008 in Changsha, China (Satoto and Sembiring 2009). Adoption of hybrid rice in Indonesia has been increasing gradually since 2005 through government programs and nongovernment programs. The objective of this chapter is to describe hybrid rice adoption and its successes and challenges in Indonesia.

Current status of hybrid rice adoption

At present, more than 80% of the rice area is planted with improved varieties and 54% of it is irrigated lowland rice. Table 1 shows the adoption of improved varieties during 2005-09. IR64 and Ciherang were the two major varieties for the 1980s and 2000s, respectively, and they covered 60% of the total planted area. Adoption of hybrid rice in Indonesia has been increasing gradually since 2005; however, the hybrids were generally susceptible to brown planthopper (BPH), bacterial leaf blight (BLB), and rice tungro virus (RTV), and they did not always express their heterosis potential across locations. The new generation of hybrid varieties showed a better performance in both experimental and farmers' fields. Up to now, 71 hybrid rice varieties have been released (Table 2). Seventeen hybrid rice varieties,namely, Maro, Rokan, Hipa3, Hipa4, Hipa5 Ceva, Hipa6 Jete, Hipa7, Hipa8, Hipa9, Hipa10, Hipa11,Hipa12 SBU, Hipa13, Hipa14 SBU, Hipa Jatim1, Hipa Jatim2, and Hipa Jatim3, were developed by the Indonesian Center for Rice Research (ICRR) as the government rice institution, while the others were developed byprivate organizations. ICRR, especially the hybrid rice research team, also collaborates with private organizations to develop

Table 1. Adoption of high-yielding varieties.

Variety	Year released	Adoption (% of total rice planted area)			
		2005	2006	2007	2009
IR64	1984	31.4	23.6	17.1	10.5
Ciherang	2000	21.8	31.3	41.5	47.6
Local varieties	–	12.9	–	–	8.4
Ciliwung	1989	8.0	3.3	4.0	4.4
Rice lines	–	5.1	–	–	–
W. Apo Buru	1998	3.3	2.3	–	–
IR42	1988	2.4	1.2	–	1.4
Widas	1999	1.8	–	–	–
Memberamo	1995	1.6	1.8	1.8	–
Cisadane	1980	1.6	3.8	–	–
IR66	1995	1.1	–	–	–
Cisokan	1985	1.1	–	–	–
Cibogo	2003	1.1	3.3	4.2	3.6
Cigeulis	2002	–	–	5.1	5.2
Cisantana	2000	–	–	2.7	–
Others	–	28.7	29.8	17.5	15.4

Table 2. Hybrid rice varieties released in Indonesia.

Institution/company	No.	Hybrid rice variety names
ICRR	17	Maro, Rokan, Hipa3, Hipa4, Hipa5 Ceva, Hipa6 Jete, Hipa7, Hipa8, Hipa9, Hipa10, Hipa11, Hipa12 SBU, Hipa13, Hipa14 SBU, Hipa Jatim1, Hipa Jatim2, Hipa Jatim3
BISI	4	Intani 1, Intani 2, Intani 301, Intani 602
BangunPusaka	2	LP Pusaka 1, LP Pusaka 2
Kondo	5	Miki 1, 2, 3; Manis 4 and 5
Bayer Crop Science	4	Hibrindo R1, Hibrindo R2, TEJ, 6444
KNB Mandiri	2	Batang Kampar, BatangSamo
Dupont	2	PP-1, PP-2
Makmur SNT	2	BrangBiji, SegaraAnak
TU Saritani	2	Adirasa-1, Adirasa-64
PT SHS and partner	11	SL8, SL11, WM2, 3, 4, 5, DG1 and 2, BSH1,3, and 6
Primasid	2	Mapan-P.02, Mapan-P.05
SAS	6	BernasSuper, Bernas Super2, Bernas Prima, 2, 3, 5
Biogene Plantation	6	Sembada B3, SB-5, SB-8, SB-9, S 101, S168
AgriMakmur Pertiwi	2	Rejo 1, Rejo2
Metahelix	2	DR1, DR2
Advanta	2	PAC801, PAC809
Total	71	21 varieties developed in Indonesia, 50 introduced from China and India

hybrid rice, to make it more widely recognized by farmers. Data taken from front-line demonstrations in 2003 showed that Maro and Rokan yielded −11% to 46% higher, with an average of 14% higher, than the check inbred variety (Ciherang yielded 9.60 t/ha), and Rokan produced 11.60 t/ha, which outyielded others by 2 t/ha (Table 3). Our experience so far has found that government support was useful, especially during the past five years. To accelerate hybrid rice adoption, a dissemination program of hybrid rice technology has begun in 16 districts that were identified as having potential for hybrid rice cultivation under the national rice production increase program (P2BN). The impact of hybrid rice technology in Indonesia was assessed by two government agencies, the Assessment Institute of Agricultural Technology located in 27 provinces under the Indonesian Agency of Agricultural Research and Development, and District Agricultural Agencies, the Directorate Cereals and Directorate General for Food Crops. Assessment of the impact was carried out in the activity called Integrated Crop Management Field School (ICM-FS). The total area of hybrid rice cultivation under the ICM-FS program is described in Table 4.

The successes and challenges of hybrid rice cultivation

Hybrid rice development in Indonesia is promising because of the availability of some determining factors such as suitable area (1.6 million ha), cultivation technology, high yield potential, 71 released hybrid rice varieties, increasing productivity, an increase in the national rice production program, and collaboration with private companies. In Indonesia, hybrid rice can be grown as lowland rice at both low and medium altitude, with the following conditions: (1) a good irrigation and drainage system, (2) light-medium soil texture, and (3) appreciative and responsive farmers. The target area for hybrid rice cultivation has the following characteristics: (1) high-yielding rice production areas, (2) an assured supply of irrigation water and good drainage, (3) fertile soils with medium to light texture, (4) non-hotspots of major insect pests (such as BPH) and diseases (BLB, RTV), (5) practices of synchronous planting techniques, (6) good accessibility to inputs (fertilizer and pesticides), and (7) progressive farmers.

Java and Bali are two potential areas for developing hybrid rice. During the dry season, as many as 33 districts covering 1,611,960 ha, equal to 32% of the total irrigation area,are suitable for planting hybrid rice, while during the wet season there are 23 districts covering 1,655,162 ha, equal to 33% of the total irrigation area.

Farmers should plant hybrid rice in a suitable area in order to have optimum yield, so that the target of development of hybrid rice could be achieved. Technically, five keys are required for developing hybrid rice: the right variety, quality seed, good cultivation techniques, suitable planting area, and skilled farmers.

Tables 5 and 6 show that, at the farmer level, local hybrids Hipa11 and Hipa8 yielded 9.93 and 9.55 t/ha, respectively, higher than inbred varieties Inpari13 (8.62 t/ha) and Inpari10 (6.45 t/ha). In other farmers' fields, Hipa11 yielded 9.21 and 10.87 t/ha, Hipa8 9.36 and 8.11 t/ha, and PP1 9.05 t/ha, which was higher than the yield of the most popular inbred at the location, Logawa, which yielded 7.83 t/ha.

Table 7 shows the yield and increase in farmers' income by planting hybrid rice in West Java for some farmers in Cianjur (a regency in West Java, suitable for planting

Table 3. Grain yield of Maro and Rokan hybrids compared with that of inbred check variety Ciherang, taken from on-farm trials, ICFORD, 2003.

Number of locations	14 districts
Average yield of Maro	7.3 t/ha
Average yield of Rokan	7.5 t/ha
Heterosis range	−11% to 46% (average 14%)
Attainable yield of Rokan	11.06 t/ha
Attainable yield of Ciherang	9.60 t/ha
Hybrid rice yield range	5.52−11.06 t/ha

Table 4. ICM-field school of rice, 2009-11.

Commodity	Description	Year		
		2009	2010	2011
Inbred	Planted (ha)	1,726,809	1,904,690	1,752,993
	Harvested (ha)	1,122,837	1,406,670	561,034
	Productivity (t/ha)	5.97	5.53	5.89
	Production (t)	6,705,626	7,782,249	3,306,155
Hybrid	Planted (ha)	46,886	186,344	140,345
	Harvested (ha)	36,778	151,757	13,505
	Productivity (t/ha)	8.31	7.04	6.24
	Production (t)	297,366	1,068,158	84,211
Total rice	Planted (ha)	1,773,695	2,355,417	2,098,551
	Harvested (ha)	1,158,615	1,744,610	582,166
	Productivity (t/ha)	6.04	5.49	5.88
	Production (t)	7,002,992	9,573,243	3,422,919

Source: Directorate Cereals (2012).

hybrid rice). The yield increase reached 15−50% more than that of inbreds from 0.25 ha to 3.5 ha in planting area or a 33−40% income increase that could be reached by farmers.

Hybrid rice faces several threats: pests and diseases (BPH, BB, RTV, stem borer, rats), identical cytoplasm of CMS lines among hybrids, highly fluctuating temperature that affects seed production, an expensive seed price, the effects of global climate change (rainfall during the flowering period) on seed production, the habit of using farmer-saved seed, and limited suitable area for hybrids.

Challenges

The following are important challenges: (1) unreasonably high farmer expectations, (2) hybrid rice quality that was less than that of inbreds, (3) unstable performance due to varied cultivation management, (4) poor resistance to pests and diseases, (5) seed

Table 5. Grain yield of some released hybrid rice varieties at the farm level, Mernek, Maos, Central Java, CS II, 2011.

Variety	Area (ha)	Farmer	Yield (t/ha)
Mapan 02	0.105	Waluyo	7.58
Mapan 53	0.105		7.96
Mapan 05	0.105		12.16
Hipa 8	0.35		8.82
Hipa 11	0.35	Barian	7.96
Hipa 8	0.35		8.72
Hipa 11	0.35	Kuswanto	8.24

Table 6. Grain yield of some released hybrid rice varieties in farmers' fields, Mernek, Maos, Central Java, CS I, 2011.

Variety	Area (ha)	Farmer	Yield (t/ha)
Hipa 11	0.107	Kuswanto	9.93
Hipa 8	0.070		9.55
Inpari 13 (inbred)	0.178		8.62
Inpari 10 Laeya (Inbred)	0.357		6.45
	0.085	Waluyo	9.21
Hipa 11	0.014		10.87
	0.357		9.36
Hipa 8	0.285		8.11
PP 1	0.017		9.05
Logawa (Inbred)	0.700		7.83

Table 7. Increases in yield and farmer income, Cianjur, West Java, WS 2010-11.

Yield (kg)				
Farmer	Area (ha)	Hybrid	Inbred	Yield increase (%)
Barnas	3.5	24,173	21,000	15
Samsudin	1.25	9,073	6,285	44
Saepulloh	0.15	1,200	800	50
Income (IDR)				
Farmer	Area (ha)	Hybrid	Inbred	Income increase (%)
Barnas	3.5	26,987,000	20,277,000	33
Samsudin	1.25	22,804,500	16,277,000	40
Saepulloh	0.15	3,000,000	2,240,000	34

quality particularly in terms of purity and viability, (6) unstable seed yield, and (7) a very high cost of seed production.

Some problems were identified for hybrid rice adoption and development in the near future: (1) unstable heterosis expression; additional locations for early evaluation will increase the chances to identify stable hybrids; (2) most hybrid rice varieties released in Indonesia were susceptible to BPH, BLB, and RTV; this contributed to the unstable performance of hybrids and thus became a constraint to hybrid rice adoption; (3) rice quality such as grain milling, broken rice, grain shape, and chalkiness; and (4) the development of indica × japonica and indica × javanica hybrids.

In general, the following points can be made: (1) seed production techniques have been developed but they have not reached the optimum level yet, (2) most released hybrid rice varieties were susceptible to major pests and diseases in Indonesia, (3) farmers had unreasonably high expectations, (4) unstable performance occurred due to improper cultivation practices and unsuitable area, (5) there was limited availability of pure seed of parental lines, (6) seed yield was unstable and the price was expensive, and (7) some farmers used their seed saved from the previous crop.

Successes

The success of hybrid rice technology depends on efficient and economical seed production on a commercial scale. Hybrid rice seed production is a skill-oriented activity; therefore, a smooth technology transfer is required to assure high seed yield. The amount of heterosis and hybrid rice adoption on a commercial scale depends on the ability to produce quality F_1 hybrid seed in a large amount. The availability, quality, and price of hybrid rice seed determine the level of adoption.

The requirements for hybrid seed production land aremedium altitude (100 to 500 m), 70−80% relative humidity, 24−28 °C daily temperature with a maximum temperature of <32 °C and 8−10 °C night-day temperature difference, sunny, 10−15 km/h wind velocity, no rain during flowering time, fertile (pH neutral) soil, and responsive farmers.

Hybrid rice seed in Indonesia was produced mainly by ICRR with the involvement of the local government and private companies. In Bukittinggi,West Sumatera, Siak, and Inderapura-Riau, seed production was done by KNBM (Karya Niaga Beras mandiri); in Lampung and Karawang by SAS;and in Banyudono, Central Java Province, seed production was done by the Province seed farm. Other locations of suitable area for producing F_1 hybrid seed appear in Table 8.

It is better to produce hybrid rice seed in the dry season (April to September), with some determining factors: dry conditions, no rain during the flowering period, optimum wind velocity, sunny, and less pests and diseases.

Synchronization of flowering is one of important factors to produce good yield of hybrid rice seed. An 80% synchronization of flowering that was achieved through the use of a blower or bamboo as supplementary pollination with or without leaf clipping produced more than 1 t/ha (1.45–1.67 t/ha) of F_1 seed; on the other hand, 30% synchronization of flowering in seed production produced only 0.66 t/ha of F_1 seed. Data taken from the seed production of hybrid rice (variety Maro) in Pusakanegara, Subang Regency, West Java, in 2002 appear in Table 9.

During 2006 to 2011, the Indonesian Center for Rice Research collaborated with and licensed hybrid rice seed with private companies for seed production. Muara Bogor, one of the ICRR farm fields, in the dry season of 2006, produced 1.1 t/ha of Maro hybrid rice seed. In 2007, the collaboration on Hipa3 seed production with

Table 8. Predicted suitable area for producing F_1 hybrid rice seed.

District	Province	Seed production done in the respective area	District	Province	Seed production done in the respective area
Bukittinggi	W. Sumatera	KNBM	Banyudono	C. Java	Prov. Seed Farm
SiakInderapura	Riau	KNBM	Sragen	C. Java	BISI
Lampung	Lampung	SAS	Malang	E. Java	Dupont, Syngenta
Karawang	W. Java	SAS	Mojokerto	E. Java	Dupont, MSNT
Sukamandi	W. Java	ICRR, SHS	Lombok	West NT	MSNT
Sidrap	South Sul	SHS-SL Agrictech	Situbondo	E. Java	Dupont
Bantul	Yogyakarta	Syngenta	Kediri	E. Java	BISI
Salatiga	C. Java	Primasid	Banyudono	C. Java	Prov. Seed Farm
Tegalgondo	C. Java	Prov. Seed Farm			

Table 9. Seed yield of Maro in Pusakanegara, West Java, DS 2002.

Leaf Treatment	Supplemental pollination	Synchronization	Yield (kg/ha)
Non-leaf clipping	Blower	80%	1,673
Leaf clipping	Blower	80%	1,728
Leaf clipping	Bamboo	30%	656
Non-leaf clipping	Blower	80%	1,451

PT Syngenta took place in Bantul Yogyakarta to produce 1.1 t/ha. Seed production of Hipa6 Jete in the dry season of 2008 in a Sukamandi field in Subang, West Java, yielded 1.8 t/ha; then, in 2009, seed production of Hipa9 yielded an amazing 2 t/ha. In the dry season and wet season of 2010-11, collaboration took place between ICRR and AIAT Sumut in North Sumatera in producing Hipa6 Jete and this yielded 0.95 t/ha, but the collaboration with PT Saprotan Benih Utama (SBU) in Maos Cilacap in producing Hipa14 SBU produced 1.7 t/ha (Table 10).

F_1 hybrid seed rice production of SL8 SHS in Sukamandi, Subang Regency, as presented in Table 11, showed that the yield of hybrid rice seed production reached 1.5 to 3.2 t/ha.

Indonesia still imports hybrid seeds, including parents and hybrids, since not enough seeds are produced. During 2005, 10.42 tons of F_1 hybrid seed or 58.54% from the avaibility of Indonesian F_1 hybrid seed were imported, while about 6.75 tons or about 54% of parental seeds were imported. In 2006 and 2007, the import of F_1 hybrid seed and parental seed increased to 102.14 tons and 3,973 tons or 76.08% and 87.03%, respectively, while parental seed increased to 8.05 tons and 13.60 tons or 48.94% and 59.91%, respectively. During 2005-10, the highest demand for F_1 hybrid seed occurred in 2009, when we imported 4,868.79 tons of F_1 hybrid seed (Table 12).

Table 10. Seed production of hybrid rice developed by ICRR.

Seed grower	Location	Season	Variety	Seed yield (kg/ha)
BB Padi	Muara, Bogor	2006 DS	Maro	1,100
PT Syngenta	Bantul	2007 DS	Hipa3	1,057
BB Padi	Sukamandi, Subang	2008 DS	Hipa6 Jete	1,800
PT Dupont	Krebet, Malang	2009 DS	Hipa8	2,000
AIAT SUMUT	MedangDeras, Kab Batubara	2010-11 WS	Hipa6 Jete	945
PT SBU	MaosLorCilacap	2011 DS	Hipa14 SBU	1,700

Table 11. F_1 hybrid seed production of variety SL8 SHS, Sukamandi.

Year	Harvest date	Area (ha)	Seed yield (kg/ha)
2008	19-9-2008	2.00	1,458
		1.00	2,215
		1.00	2,566
		1.00	3,919
		1.00	2,873
	21-9-2008	2.00	2,272
		1.00	2,779
		1.00	2,774
		1.79	1,932
		0.50	1,620
2008	9-9-2008	2.00	2,252
		1.67	3,001
		1.50	2,552
	11-9-2008	2.00	1,916
		2.00	1,964
	24-9-2008	1.00	2,353
		1.75	2,845
		2.00	3,165
	15-9-2008	1.00	2,672

On a commercial scale, seed yield still varied, with an average of 1.2 t/ha. A seed system suitable for hybrid rice, including seed production, inspection, and certification, has been established. Nevertheless, there are still some threats to hybrid rice development in Indonesia, such as (1) pests and diseases, particularly BPH, BLB, RTV, and stem borer; (2) the CMS used to develop hybrid rice varieties possessed the same cytoplasm type; (3) the environmental temperature fluctuates a lot, resulting in difficulties in seed production; (4) an expensive seed price; (5) the impact of climate change, that is, high rainfall during the flowering stage will affect seed production; (6) the habit of some particular farmers to use their own seeds; and (7) limited suitable areas for hybrid rice cultivation as well as seed production.

Table 12. Imported F_1 hybrid and parental seed during 2005-06.

Year	Imported seed			
	F_1 hybrid seed		Parental seed	
	Tons	%	Tons	%
2005	10.42	58.54	6.75	54.00
2006	102.14	76.08	8.05	48.94
2007	3,973.00	87.03	13.60	59.91
2008	3,321.50	84.61	32.81	82.64
2009	4,868.79	87.87	30.10	53.01
2010	3,364.15	66.62	2.13	2.18
Total	15,640.00	81.32	93.44	38.04

Hybrid rice seed production has challenges and alternative solutions. Actually, it is not easy to produce hybrid rice seed, and we face several challenges.The sustainability of parental seed stock is one challenge, which can be solved by responsible NS/BS production and delivery through the *paired crossing method*, which should be done by the institutions where hybrids are released and the foundation seeds of the parents of public hybrids that must always be available, and this needs to be developed by institutions for this purpose. The other is limited trained human resources. To solve this problem, we can do more orientation on practical matters and effective training for the right seed growers, and these must be better organized. Low seed productionis also an important thing to solve as achallenge, and this could be solved by good synchronization, good agronomic management in each seed production block, and all recommended packages should be implemented effectively. Simple storage methods should be identified and adopted. Medium- and long-term seed storage facilities must be developed as those are the solutions tothe challenge of a short storage period of F_1 and parental seed. Adoption of molecular techniques to test purity is needed to solve the challenge of time-consuming grow-out tests. The final challenge is the high cost of seed production. This could be solved by increasing seed production by adopting all recommended seed production packages and searching for and adopting cheaper alternatives to GA3. It is also urgent to develop high outcrossing potential of CMS.

In order to get "the perfect" hybrid rice seed, besides solving the challenge, things that we can do in the future as main priorities are to increase average seed yield up to 2.0 t/ha, reduce production costs, identify suitable areas for seed production on a commercial scale,improve the education of human resources, and motivate public seed growers for more contributions. This could be achieved through the right policy and full support from the government.

Conclusions

1. To increase national rice productivity and to achieve the target of 2011-14 of increasing rice production by 5% per year and having a surplus of 10 million

tons of milled rice in 2014, the use of hybrid rice varieties is one important thing that should be done. Adoption of hybrid rice in Indonesia has increased gradually since 2005.
2. The right variety, good-quality seed, good agricultural practices, suitable area, and farmers' eagerness are five key factors in hybrid rice development so the direction and the objectives of hybrid rice development are to obtain superior hybrid varieties that are very adapted in the environment of Indonesia, and that have resistance to all the main pests and diseases and better eating quality.
3. The seed system and seed technology had been developed, but they are not optimal yet.
4. Released hybrid varieties are mostly susceptible to major pests and diseases in Indonesia.
5. Farmers have high expectations.
6. Performance is not stable due to different agricultural practices and inappropriate environment.
7. Pure seed of parents and F_1s is sometime not available.
8. Yield is not so stable and the seed price is expensive.
9. Farmers tend to use seed from previous cropping (F_2).

Suggestions

The future direction of hybrid rice development is to breed hybrids that are really adapted for Indonesia, with resistance to major pests and diseases and better eating quality. These could be developed by the use of local germplasm collections or combining national and introduced lines.

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Hybrid rice in the Philippines

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Rice self-sufficiency is a very challenging goal for the Philippines. With limited land resources, it has a relatively small area harvested to rice compared with other Southeast Asian countries such as Vietnam and Thailand. This is made even more difficult by the rapidly increasing population, at a rate of at least 2% per year. In 2009, the Philippines fed 20 people per hectare of rice area harvested in contrast to 6 people for Thailand and 12 for Vietnam (Philippine Rice Industry Primer Series 2011).

What the Philippines lacked in area harvested to rice, it has compensated for terms of yield growth. Rice production grew significantly at 3% per year in the last decade and followed Vietnam's 2.3% in terms of annual yield growth with 2.2% in the 2000s (Department of Agriculture 2011).

With the appropriate technologies and advances in rice science, increasing productivity is one of the major strategies to meet the demand for rice. The government aims to produce 22.73 million tons by 2016, an average growth of 6% per year (Department of Agriculture 2011).

Overview

The introduction of hybrid rice technology in the Philippines in 1998 was welcomed with great expectations. On the same irrigated rice production area, a farmer can get as much as a 15% yield advantage over the best inbred variety. In China, 20 million t of additional paddy were being produced annually at the time (Virmani and Toledo 2000), which contributed to its food security.

Research and development (R&D) in hybrid rice in the Philippines started as early as the 1970s at the International Rice Research Institute (IRRI). More than a decade later, the Philippine Rice Research Institute (PhilRice) followed suit. This was prompted by a visit by Professor Li Zhengyou, director of the Yunnan Agricultural University Rice Research Institute, in 1988, who offered to help PhilRice to propagate the technology (Gaspar et al 2007).

This visit opened the door to various collaborative work between the Philippines and China on hybrid rice. One of these is the memorandum of agreement (MOA) with Yunnan Agricultural University on hybrid rice R&D in the Philippines focusing on germplasm exchange and evaluation, the development of hybrid rice and inbred rice varieties, and cultural management technologies. PhilRice has also forged linkages with the Jiangxi Academy of Agricultural Sciences and Guangxi Academy of Agricultural Sciences in hybrid rice technology development (Gaspar et al 2007).

Other collaboration came later such as the Technical Cooperation Project (TCP) grants from the Food and Agriculture Organization of the United Nations (FAO) from 1998 to 2000. These projects helped strengthened the country's capacity for hybrid rice development and use (Redoña et al 2003).

IRRI released the first hybrid variety in the Philippines in 1994, PSB Rc26H (Magat). This was followed by PSB Rc72H (Mestizo), a variety also developed by IRRI, in collaboration with PhilRice. Meanwhile, Monsanto released the first private hybrid variety in 1998, PSB Rc76H (Panay).

Soon after, the opportunity to promote the technology presented itself through the *Gintong Ani* Hybrid Rice Program of former President Fidel V. Ramos in 1998. The program was composed of research and development, extension and promotion, and seed production and commercialization (Gaspar et al 2007).

A bigger and more comprehensive Hybrid Rice Commercialization Program (HRCP) was formulated and launched in 2001 by former President Gloria Macapagal-Arroyo with the goal of promoting the widespread use of hybrid rice seed technology to enhance productivity and income (Gaspar et al 2007).

PhilRice then intensified its research activities toward strengthening the hybrid rice program and providing technical assistance to prospective farmers and seed growers. Collaboration such as that with IRRI, Chinese research institutions, and other local and international networks was further strengthened in order to enhance PhilRice's research and training capability (Gaspar et al 2007).

The Hybrid Rice Commercialization Project: accomplishments and impacts

With the increasing pressure to produce more rice for Filipinos, the government recognized the potential of hybrid rice technology to increase production and launched the HRCP on 4 March 2002. PhilRice served as the lead implementing agency (Gaspar et al 2007).

This program has three major objectives: (1) reduce the importation of rice and attain self-sufficiency in the crop, (2) increase rice production with less land and improve farm yields, and (3) create employment opportunities in the rural areas (STRIVE and PhilRice 2007).

During the implementation of the HRCP, hybrid rice production increased and made a significant contribution to national production (Table 1). From 168,659 tons in 2002, production almost tripled to 461,847 t in the following year. In 2005, production of hybrid rice was at its highest at 2.2 million t, contributing 15% to total rice production (14.6 million t). Meanwhile, in 2008, hybrid rice contributed 1.3 million t (8%) to national production, which was 16.8 million t.

The government's continued efforts to promote hybrid rice technology were evident as the area planted to hybrid rice increased markedly. From 5,472 ha in 2001, it expanded to 374,260 ha in 2005, making the Philippines the country with the fourth

Table 1. Hybrid rice area, production, and yield, 2001-10.

Year	Area planted (ha)	Production (t/ha)	Total production (t/ha)	% Contribution	Yield (t/ha)
2001	5,472	29,223	12,954,870	0.2	5.44
2002	28,375	168,659	13,270,653	1.3	6.04
2003	80,055	461,847	13,499,884	3.4	5.97
2004	208,884	1,172,863	14,496,784	8.1	5.75
2005	374,260	2,213,818	14,603,005	15.2	6.01
2006	319,873	1,829,874	15,326,706	11.9	5.87
2007	241,981	1,462,938	16,240,194	9.0	6.13
2008	224,249	1,349,282	16,815,548	8.0	6.06
2009	201,264	1,179,107	16,266,417	7.2	6.12
2010	204,022	1,362,867	15,772,319	8.6	6.68
Total	**1,888,435**	**9,867,611**	**149,246,380**		

Source: Department of Agriculture, Bureau of Agricultural Statistics.

biggest area planted to hybrid rice (Gaspar et al 2007). The average yield for hybrid rice also increased from 5.44 t/ha when the HRCP started in 2002 to 6.68 t/ha in 2010, at a rate of 80 kg/ha annually.

Along with the increase in area planted and production of hybrid rice, it has also continuously performed better than inbred rice (Table 2) with a 1.16–2.40 t/ha yield difference. When the program started, the yield advantage was 1.16 t/ha but, after several years of technology promotion and advancements in hybrid rice R&D, the yield advantage at the farm level reached about 2.40 t/ha in 2010.

The social impacts of the HRCP were also assessed through a joint midterm evaluation of the program by PhilRice and the Society towards Reinforcing Inherent Viability for Enrichment (STRIVE) Foundation from 2002 to2004. The emphasis was on profitability and productivity.

According to the study, at the farm level, the total production cost per hectare was 8–13% higher for hybrid rice because of the additional expenses for inputs such as seeds, fertilizers, and chemical pesticides, as well as additional labor requirements. With time, these farmers became more cost-efficient after gaining knowledge and experience (STRIVE and PhilRice 2007).

In a more recent survey conducted by PhilRice from 2005 to 2007 (Table 3), production costs for hybrid rice reached as much as Php30,000–40,000/ha compared with those of inbred rice, which were Php29,000–35,000/ha during the wet season. Net profit was also higher for hybrid rice (P21,000–33,000) than for inbreds (P15,000–17,000).

Farmers incurred more expenses in the dry season spending as much as P37,000–50,000/ha for hybrid rice and P31,000–46,000/ha for inbred rice. They also earned a much bigger net profit, ranging from P26,000 to PhP50,000 for hybrid rice. For inbred rice, net profit was P14,000–29,000 during the dry season.

Table 2. Yield difference between hybrid rice and certified seeds, 2001-10.

Year	F_1		Certified seeds		Yield difference	
	Area harvested (ha)	Yield (t/ha)	Area harvested (ha)	Yield (t/ha)	(t/ha)	(%)
2001	5,472	5.44	599,961	4.28	1.16	27.07
2002	28,375	6.04	1,283,012	4.43	1.61	36.28
2003	80,055	5.97	1,233,210	4.47	1.50	33.43
2004	208,884	5.75	1,083,290	4.57	1.18	25.75
2005	374,260	6.01	915,095	4.54	1.46	32.20
2006	319,873	5.87	1,010,211	4.48	1.40	31.26
2007	241,981	6.13	1,584,705	4.35	1.78	40.82
2008	224,249	6.06	1,733,654	4.43	1.63	36.85
2009	201,264	6.12	2,522,046	4.18	1.94	46.32
2010	204,022	6.68	599,961	4.28	2.40	56.07
Average	188,844	5.98	1,256,515	4.40	1.61	36.32

Source: Department of Agriculture.

Table 3. Comparative costs and returns of hybrid and inbred rice production, wet season, 2005-08.

Items	WS 2005			WS 2006			WS 2007		
	Hybrid	Inbred		Hybrid	Inbred		Hybrid	Inbred	
Average area (ha)	2.30	1.41		2.23	1.73		1.65	1.89	
Returns									
Yield (t/ha)	5,643	5,075		5,431	5,003	*	6,186	5,216	***
Price per kg (Php)	9.10	8.70	***	10.00	9.50	***	11.70	9.90	***
Gross returns (Php)	51,178	44,054	**	54,374	47344	**	72,127	51,544	***
Costs									
Total production cost (Php)	30,237	28,873		33,484	31,228		39,574	34,979	**
Cost per kg (Php)	5.36	5.69		6.17	6.24		6.40	6.71	
Net profit (Php)	20,941	15,182	**	20,891	16,116	*	32,553	16,565	***
Net profit-cost ratio	0.69	0.53		0.62	0.52		0.82	0.47	

Significance: * = 1%; ** = 5%; *** = 10%.
Source: PhilRice.

The prospect of increasing their yield and income enticed a lot of farmers to adopt hybrid rice technology. Its introduction provided Filipino farmers with an option to produce more and earn more. Although hybrid rice requires more inputs than inbred rice cultivation, those who grew it learned to "optimize hybrid rice production, at less cost (STRIVE and PhilRice 2007)."

Impacts were not limited to monetary gains as hybrid rice farmers acquired skills and techniques on seedbed preparation and seedling management. This resulted in a higher level of confidence in discussing rice-related issues with other people. At the same time, hybrid rice cultivation, they learned, is more than just about using hybrid seeds. It is a process, a whole package of rice production technologies—recommended seeding rate, synchronous planting, pest and disease management, and other related cultural management practices—that are different from those for inbred cultivation (Sebastian et al 2006).

Hybrid rice research and development: focus and directions

During the introduction of hybrid rice technology, PhilRice created an R&D program for hybrid rice in 1998 with the main goal of developing and using the technology to increase yield by at least 15%. This multidisciplinary approach included breeding; seed production, nutrient, water, and pest management; socioeconomics; and policy and other related fields. The program also focused its efforts on the following: (1) the development and promotion of resource- and cost-efficient seed production technologies for parental and hybrid seed production; (2) information, education, and communication activities aimed at both the general public and farmers; (3) coordination of public-sector activities on hybrid rice with the private sector; and (4) forging linkages with international institutions and programs focused on hybrid rice.

At present, the hybrid rice R&D strives to help the country attain rice self-sufficiency through the development of high-yielding varieties with excellent eating quality and resistance to pests and diseases. Likewise, hybrid rice breeding at PhilRice hopes to maximize the benefits to society that could be derived from the cultivation of public hybrid rice varieties. Twenty varieties (Table 4) developed by the public sector are available to farmers for cultivation.

Farmers' acceptance of F_1 seed in rice production has led to a growing seed industry with numerous private businesses (Table 5), many of which are multinational companies.

The government seeks to sustain access to seeds of hybrid rice varieties that are relatively affordable and with excellent agronomic performance to as many farmers as possible to ultimately increase farm productivity and help the country attain rice self-sufficiency.

One of the recent efforts in this direction is the launch of the National Hybridization Program in 2011 by the Department of Agriculture (DA) to provide better competition and cheaper hybrid rice seeds to farmers. This program is working with PhilRice and other DA research stations to plant 50,000 ha with NSIC Rc202H (Mestiso 19) and NSIC Rc204H (Mestiso 20) and it is expected to produce 375,000 t of rice seeds.

Table 4. Public hybrids developed in the Philippines, 1994-2011.

Hybrid	Released as	Breeder	Year released
1. Magat	PSB Rc26H	IRRI	1994
2. Mestizo	PSB Rc72H	IRRI	1997
3. Mestiso 2	NSIC Rc114H	IRRI	2002
4. Mestiso 3	NSIC Rc116H	IRRI	2002
5. Mestiso 7	NSIC Rc136H	IRRI	2006
6. Mestiso 12	NSIC Rc174H	PHILSCAT	2008
7. Mestiso 13	NSIC Rc176H	PHILSCAT	2008
8. Mestiso 14	NSIC Rc178H	PHILSCAT	2008
9. Mestiso 16	NSIC Rc196H	PhilRice	2009
10. Mestiso 17	NSIC Rc198H	PhilRice	2009
11. Mestiso 19	NSIC Rc202H	PhilRice, UPLB	2009
12. Mestiso 20	NSIC Rc204H	PhilRice, UPLB	2009
13. Mestiso 21	NSIC Rc206H	IRRI	2009
14. Mestiso 25	NSIC Rc230H	IRRI	2010
15. Mestiso 26	NSIC Rc232H	IRRI	2010
16. Mestiso 29	NSIC Rc244H	PhilRice	2011
17. Mestiso 30	NSIC Rc246H	IRRI	2011
18. Mestiso 31	NSIC Rc248H	IRRI	2011
19. Mestiso 32	NSIC Rc250H	PhilRice	2011
20. Mestiso 38	NSIC Rc262H	PhilRice, PHILSCAT, CLSU	2011

Source: PhilRice.

Hybrid rice breeding at PhilRice

The objectives of the hybrid rice breeding project are as follows: (1) produce the basic germplasm needed in breeding new hybrids, (2) develop and test two- and three-line hybrids with high yield potential for commercial release, (3) optimize the efficiency of parent line and hybrid seed production protocols, and (4) conduct technology demonstration for wide-scale promotion and adoption of new hybrid varieties.

Primarily designed for favorable irrigated lowland environments, high yield potential is the principal reason for hybrid rice breeding. To support a yield target of 12 t/ha, a plant architecture with strong culm and thick and erect leaves must be developed. Restoring ability, pollen load, and outcrossing rate are the major considerations in developing parental lines. Disease resistance to bacterial leaf blight (BLB) and tungro, a major drawback to early hybrid varieties, is beginning to be addressed to minimize yield loss, especially during the wet season. BLB is the most predominant disease in the current hybrid varieties released in the Philippines.

For grain quality, the focus is primarily on chalkiness since it has a great impact on the pricing of paddy rice produced by farmers. Millers have been downgrading the price of paddy rice of hybrid rice varieties due to chalkiness. PhilRice also seeks to

Table 5. Private hybrids developed in the Philippines, 1994-2011.

Hybrid	Released as	Breeder	Year released
1. Panay	PSB Rc76H	Monsanto	1998
2. Mestizo 4	NSIC Rc124H	Bayer	2004
3. Mestiso 5	NSIC Rc126H	Monsanto	2004
4. Mestiso 6	NSIC Rc132H	SL Agritech	2004
5. Mestiso 8	NSIC Rc162H	Bioseed	2007
6. Mestiso 9	NSIC Rc164H	HyRice	2007
7. Mestiso 10	NSIC Rc166H	Syngenta	2007
8. Mestiso 11	NSIC Rc168H	Bayer	2007
9. Mestiso 15	NSIC Rc180H	Bioseed	2008
10. Mestiso 18	NSIC Rc200H	Bayer	2009
11. Mestiso 22	NSIC Rc208H	Syngenta	2009
12. Mestiso 23	NSIC Rc210H	Pioneer	2009
13. Mestiso 24	NSIC Rc228H	HyRice	2010
14. Mestiso 27	NSIC Rc234H	Syngenta	2010
15. Mestiso 28	NSIC Rc236H	Seedworks	2010
16. Mestiso 33	NSIC Rc252H	Advanta India Ltd.	2011
17. Mestiso 34	NSIC Rc254H	Advanta India Ltd.	2011
18. Mestiso 35	NSIC Rc256H	Beidahuang Seed	2011
19. Mestiso 36	NSIC Rc258H	Metahelix/Dhaanya	2011
20. Mestiso 37	NSIC Rc260H	Seedworks	2011
21. Mestiso 39	NSIC Rc264H	Metahelix/Dhaanya	2011
22. Mestiso 40	NSIC Rc266H	DevGen	2011
23. Mestiso 41	NSIC Rc268H	DevGen	2011
24. Mestiso 42	NSIC Rc270H	DevGen	2011

Source: PhilRice.

increase the milling potential from 62–65% to about 70% and continue to maintain an intermediate amylose content. Other characteristics that may be important traits for the future, such as tolerance of abiotic stresses, are also considered.

To achieve these targets, hybrid rice breeding aims to capitalize on the gains already made from developing inbred varieties. This would entail extensive characterization of elite inbred breeding materials for their suitability as parental lines (i.e., sterility-maintaining and fertility-restoring abilities) and as a source of other important morpho-agronomic traits. Through trait discovery and prebreeding, the genetic base of the breeding germplasm pool is widened by the introgression of yield-enhancing traits from japonica and wild rice derivatives. This strategy is supported by the use of biotechnology and new breeding tools.

For enhanced product delivery, the first strategy is to strengthen seed production research and the support system to increase seed yield and productivity in hybrid seed production. Seed production research aims to develop high seed yield protocols at various sites with different climatic conditions, matching specific seed production technologies with potential areas for producing hybrid seed. Partnership with private seed companies is seen as one modality to improve seed production amounts and at the same time ensure the security of parental line germplasm.

The second strategy for product delivery is aggressive testing by increasing the number of test entries and number of test locations nationwide. In doing so, the adaptability of different hybrid varieties to particular types of irrigated lowland environments will be determined, and new high-yielding areas suitable for hybrid rice production will be identified. In addition, the cultivated area planted to hybrid rice will be expanded by performance testing in potential favorable rainfed lowland ecosystems.

Future directions

The growing participation of private seed companies in the Philippines means that the rice seed industry will become more and more a free market. Demand for hybrid seed will depend not only on seed quality and variety performance but also on heavy promotion by sales people that come with various marketing strategies. The DA-Regional Field Units (DA-RFUs) will play an important role in making sure that farmers are getting the kind of seed that is promised to them by both private seed companies and seed growers of public hybrids. Seed companies must abide by self-regulation and truthful labeling of their products. PhilRice branch stations and DA-RFUs will work hand in hand to build local capacity for seed production by individual seed growers and farmer cooperatives.

The rich germplasm base of PhilRice for both two-line and three-line systems must be coupled with strong variety development and commercialization for long-term sustainability. Partnership with private stakeholders, such as in terms of nonexclusive licensing of hybrids and joint seed production ventures, is envisioned as a key component of hybrid rice breeding. This collaborative mode is also expected to cover basic research involving new breeding technologies for trait discovery and line development.

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Potentials and limitations of hybrid rice production in Sri Lanka

S.W. Abeysekera and S.N. Jayawardena

Sri Lanka needs to increase its current rice production of 3.65 million tons to 4.56 million tons to meet rice demand in 2020. Since the possibilities of expanding rice land are limited, the only way is to increase the productivity of rice, for which hybrid rice is the most feasible option. The Rice Research and Development Institute (RRDI) started a hybrid rice research program in 1980 with the objectives of developing a technological package for hybrid rice that will yield 15–20% more than existing high-yielding varieties. During the last 30 years, especially in the last 10 years, RRDI has made significant achievements in hybrid rice research and development mainly by developing four cytoplasmic male sterile (CMS) lines (BgCMS1A, BgCMS2A, BgCMS3A, BgCMS4A) with desirable characters and seven restorer (R) lines (Bg1R, Bg2R, Bg3R, Bg4R, Bg5R Bg7R and Bg9R) that are prerequisites for the development of hybrids. Two hybrids, Bg 407H, with a yield potential of 13 t/ha and a 4-month-age variety (released in 2005), and BgHR8, a 3.5-month-age variety (yet to be released), were also developed using the above CMS and R lines. In addition, 13 early-maturing new hybrid combinations have been developed and evaluations are being conducted to study their grain quality and tolerance of biotic stresses. Cultural practices such as nursery seed rates, transplanting distances, and fertilizer applications for hybrids as well as F_1 seeds have also been developed. Hybrid seed production technology has been transferred to farmers and average seed yield (F_1) of 0.7 t/ha has been obtained (this yield is comparatively lower mainly due to the poor outcrossing rate of the CMS lines used to develop the particular variety). In 2009-10, a new approach ("Saruketh, a hybrid rice yaya program") started with the aim of self-production of F_1 seeds and satisfactory progress was achieved. Besides the research, several other development activities, such as training of officers and farmers on hybrid rice seed production, preparation of a training manual, and production of a video on F_1 seed production, were also undertaken. Inadequacy in scientific staff, nonavailability of suitable separate lands for seed production, and a lack of heterotic genetic materials are the major problems that need immediate attention to get the expected benefits from this program. The low outcrossing of currently available CMS lines also needs to be overcome. Good restorers need to be improved through either foreign genetic materials or some other mechanisms such as anther culture, molecular markers, and transgenic technologies. The public sector alone can do little in hybrid rice development. Therefore, private-sector involvement in hybrid rice production is urgently needed. Current policies on seed imports and other relevant matters need to be changed accordingly. Hybrid rice research and development should be the top-priority program of the Department of Agriculture of Sri Lanka and a separate unit/center for hybrid rice research and development should be established.

Keywords: Hybrid rice, CMS lines, restorer lines, self seed production, outcrossing rate

Among the many avenues available, the most effective and economic route to increasing rice production now seems to be the development and use of hybrid varieties. Through hybrid rice technology, yield potential can be increased by 1 to 1.5 t/ha beyond the limits of semidwarf high-yielding varieties (HYVs). This technology has been successfully developed and commercialized in China since 1976. China, with more than 50% of its total rice area under hybrid rice cultivation, has successfully demonstrated the application of hybrid rice technology to increase production, income, and farm employment (IRRI/ADB 2002). Following success with three-line hybrid rice in the 1970s, China successfully commercialized two-line hybrid rice in 1995. Two-line hybrid rice has a 5% to 10% yield advantage over existing three-line hybrid rice. The super rice research program initiated in 1996 has made encouraging progress to date. Several pioneer super hybrids with a yield advantage of around 20% over current three-line hybrids have been developed. Hybrid rice has proved successful in China and other countries such as Vietnam and India. With the high rate of adoption of hybrid rice cultivation, Vietnam has become the second largest rice-exporting country in Asia. Furthermore, many other countries, such as the Philippines, Bangladesh, Indonesia, Pakistan, Ecuador, Guinea, and the United States, have also made great progress in expanding hybrid rice cultivation.

The rice sector in Sri Lanka

Sri Lanka needs to increase its current rice production of 3.65 million tons to 4.56 million tons to meet rice demand in 2020. During the last two decades, the rice sector has undergone unprecedented challenges. Diminishing profitability due to the increasing cost of production, low and stagnating yield leading to low returns to investment, declining rice area because of abandoning or converting rice land for other purposes, and declining labor for rice are some of them (Silva 2010). Since the possibilities of expanding rice lands are limited, the only way is to increase the productivity of rice, for which hybrid rice technology has been identified as one possible option to increase rice yield in the country (Abeysekera et al 2000). The Rice Research and Development Institute (RRDI) initiated its hybrid rice research program in 1980. During the last 30 years, RRDI has made significant achievements in the hybrid rice research and development sector. This paper highlights past attempts, achievements, and failures and the problems to be overcome for a successful hybrid rice program in Sri Lanka.

Stages in hybrid rice research and development activities of Sri Lanka

Early phase: RRDI commenced its hybrid rice research program at RRDI (then the Central Rice Breeding Station) in the early 1980s. The unavailability of exploitable genetic materials and insufficient resources hindered the progress of this program. Then, the hybrid program restarted in 1994 with the objectives to develop high-quality Sri Lankan rice hybrids using adaptable CMS and F_1 seed production procedures and suitable cultural management practices for Sri Lankan hybrids (Abeysekera et al 2008).

Chinese phase: In 1996, RRDI and Zechuan University of China initiated a hybrid rice research program to find out the suitability of Chinese hybrid rice genetic materials under local conditions. After 4 years of research, it was revealed that Chinese genetic material could not be directly introduced to Sri Lanka.

IRRI project phase: From 1998 to 2005, RRDI received funds for hybrid rice development in two phases. In the first phase from 1998 to 2002, funds were received through the IRRI-ADB project on "Development and use of hybrid rice in Asia" and, in the second phase from 2002 to 2005, funds were received through the project on "Sustaining food security in Asia through the development and dissemination of hybrid rice technology." With this, more emphasis was given to the hybrid rice research program and as a result several CMS lines and restorers were identified and developed locally. During the second phase of the project, several experimental hybrids were developed and a small-scale F_1 seed production program was started (Abeysekera et al 2008). In 2005, the first Sri Lankan hybrid rice variety, Bg407H, was released and large-scale seed production of Bg407H began.

FAO project phase (2007-09): In 2007, RRDI received funds from FAO through a Technical Cooperation Program (TCP) on "Strengthening National Capacity for Hybrid Rice Development and Use for Food Security and Poverty Alleviation" to (1) transfer hybrid rice technologies to farmers for a rapid increase in national rice production, (2) strengthen national capacity in hybrid rice development, (3) strengthen hybrid rice F_1 seed production, and (4) formulate a medium-term national program for the development and use of hybrid rice in the country.

Progress

Improvement of parental lines

Development of CMS lines. The three-line system has been identified as a feasible system for hybrid rice in Sri Lanka. In this system, CMS lines (A) and their maintainer (B) lines and restorer (R) lines are important. The development of CMS lines with desirable characteristics and high outcrossing ability is the most important step in hybrid rice development because the hybrid rice industry primarily depends on the F_1 seed yield. Studies conducted with 53 IRRI, Indian, and RRDI CMS lines at RRDI during the minor season of 2001 and major season of 2001-02 found that panicle exsertion rate, spikelet opening angle, and duration had a significant influence on outcrossing rate under local conditions (Abeysekera et al 2003). Based on these results, two CMS lines, PMS 11A and Khrisna, from India and six CMS lines from IRRI, IR68281A, IR68897A, IR69623A, IR69616A, IR69625A, and IR68895A, have been identified as adaptable and stable under local conditions. Some of these good CMS lines were used to develop local CMS lines. During the 2001-02 major season, several Indian, IRRI, and locally developed CMS lines were evaluated at RRDI. CMS line Krishna from India, two CMS lines from Batalagoda (BgCMS1 and BgCMS2), and 28 CMS lines from IRRI have been identified as stable for both pollen and spikelet sterility and they are adaptable under Sri Lankan conditions. Two CMS lines (BgCMS1A and BgCMS2A) developed at RRDI have small round (samba) grain type with 100% sterility. BgCMS1A and BgCMS2A have an outcrossing rate of 25–27%. These locally developed CMS lines were used to develop experimental hybrids (Table 1). The program for the development of local CMS lines was continued and, as a result, four CMS lines (BgCMS1A, BgCMS2A, BgCMS3A, and BgCMS4A) have been developed (Abeysekera et al 2003).

Development of CMS lines with higher outcrossing rates. One of the drawbacks of the CMS lines developed by RRDI is the low outcrossing rate (20%). Assistance received from China in 2009 under the FAO/TCP project helped to initiate a program to develop CMS lines with higher outcrossing rates (30–40%) using TeA (33 5) and 75AYLD 12 A.

Development of maintainer lines. Initially, several selected local varieties/lines were identified as maintainer lines for some of the adaptable CMS lines and were backcrossed to their CMS sources. The most promising restorers developed were Bg99-1757, Bg98-665, Bg98-1684, Bg91-2864, Bg92-979, Bg98-3278, Bg99-700, At95-2-1 (IR68281B/Bg 1528), IR68275B/At354, Ob 2552/Bg12-1/Bg 379-1, and IR69628B/ Bg94-4516. CMS lines are being developed in the genetic background of these maintainers.

Development of restorer lines. The development of restorer lines is one of the important steps in hybrid rice development. Many high-yielding locally developed elite lines have been tested for restoring ability along with some restorers from IRRI

Table 1. Characteristic features of two CMS lines developed at RRDI.

CMS line	DFF (days)	HT (cm)	PN	PL (cm)	PE (%)	TS	OCR	Grain type
Bg CMS 1	85	77.0	15.2	21.4	80.0	231.1	29.0	Long
Bg CMS 2	76	90.0	13.6	22.4	100.0	203.2	27.0	Small
Bg CMS 3	77	96.7	15.3	26.0	83.6	242.0	25.0	Small
Bg CMS 4	69	73.2	12.2	23.2	78.0	202.0	22.0	Long

DFF = days to 50% flowering, HT = plant height, PN = panicle number, PL = panicle length, PE = panicle exsertion, TS = total spikelets/panicle, OCR% = outcrossing rate.

and the Bangladesh Rice Research Institute (BRRI). The identified restorers (IR34686-179-1-2IR, IR50360-121-3-3-3R, IR29732-143-3-2-1-R, IR60819-34-2R, IR65575-47-2-1-9R, IR62653-8-3-3R, IR40750- 82-2-2-3R, BR 168-2B-23R, and H4) are being maintained and multiplied for producing hybrids. Recently, five restorer lines, Bg1R, Bg2R, Bg3R, Bg4R, and Bg5R, have been developed at RRDI. Bg1R was used to develop the first rice hybrid variety, Bg407H, and Bg4R was used to develop new early-maturing hybrid variety BgHR8. Bg3R is a good "samba"-type restorer with desirable characters and therefore it has been included in the NCRVT (National Coordinated Rice Varietal Testing) and VAT (Varietal Adaptability Testing) programs for the testing of suitability for release as an inbred variety and at present it is in the large-scale varietal testing stage.

Development of hybrids

Cytoplasmic genetic male sterility (CMS) is the most effective and stable system used to develop hybrids. The following three hybrids, BgHR1 (long slender grains with red pericarp), BgHR6 (long slender grains with white pericarp), and BgHR12 (long slender grains with white pericarp), were developed and yield trials conducted in target areas to test their adaptability (Abeysekera et al 2003).

Two hybrids, BgHR12 and BgHR6, recorded a significant yield advantage of 2 and 1.6 t/ha over popular inbred variety Bg403 (Mahasen) in the 2003-04 major season in large-scale demonstration trials at RRDI (Abeysekera and Abeysiriwardena 2000). The growth duration of BgHR1 was comparatively longer (> 4 months) than that of the other two hybrids and seed production was difficult as the restorer (H4) was a mild photosensitive variety. The pollen fertility of the CMS line used to develop BgHR12 was not stable and therefore maintaining purity of the F_1 seed was a problem. Therefore, these two hybrids were kept aside for future improvement and BgHR6 was selected as a suitable experimental hybrid, seed production activities started, and it was submitted for testing to the NCRVT and VAT programs before commercialization. Based on its better performance, BgHR6 was released in 2005 as Bg407H. This was the first hybrid rice variety developed and released in Sri Lanka.

An early-maturing hybrid variety. The first hybrid rice variety (Bg407H) has 4-months' duration and was not suitable for many rice ecosystems due to the non-availability of water for a longer period. There was a need to develop an HR variety with 3–3.5 months' duration and therefore work on short duration began. As a result, a high-yielding, early-maturing (3.5 months) hybrid variety, BgHR8, was developed and is now in the testing stage before release (Table 2).

Grain quality characteristics of hybrids. Quality is one of the key factors that determine consumer acceptance of hybrids. Therefore, milling recovery, eating quality, and other grain quality characteristics of three hybrid rice varieties, BgHR1, BgHR6 (Bg407H), and BgHR12, developed at RRDI and tested during the 2000-01 major season revealed that total milled rice percentage and other characters were not much different from those of inbred rice. BgHR6 was the best in terms of appearance, having low translucent grains and high head grain recovery (Satraj and Abeysekera 2001).

Performance of elite Indian rice hybrids. Eight hybrids from India and three locally developed experimental hybrids (BgHR1, BgHR6, and BgHR12) were tested with

Table 2. Performance of 105-day-old hybrid Bg HR8 during the minor seasons of 2009 and 2010 and major season of 2009 at RRDI, Batalagoda.

Variety	Minor 2009		Major 2009-10		Minor 2010*	
	Maturity duration	Yield (t/ha)	Maturity duration (days)	Yield (t/ha)	Maturity duration (days)	Yield (t/ha)
Bg 300	104	3.6	98	2.6	103	4.4
Bg 357	117	3.9	108	3.6	115	5.3
Bg 379/2	—	—	125	3.3	124	4.5
Bg 407H	133	5.5	123	5.3	129	5.6
Bg HR8	112	5.0	106	5.1	112	6.0

Source: Jayawardena and Abeysekera (2009).

Table 3. Performance of Indian hybrids at RRDI during the minor season of 2010.

Variety	Maturity duration (days)	Yield (t/ha)
CRH 501	107	1.1
CRH 502	103	3.8
PAC 801	102	4.5
PAC 835	96	4.0
PAC832	113	1.6
Swarna (1)	117	4.0
Swarna (2)	110	3.6
Bg 357 (inbred check)	106	3.2
Bg HR8 (hybrid check)	100	5.4
Bg 407H (hybrid check)	128	3.5

three standard popular inbred varieties for yield and other characteristics during the 2002-03 major and 2003 minor seasons at the Field Crop Research and Development Institute (FCRDI) (dry zone) and at RRDI (intermediate zone). Significant grain yield differences among varieties were observed at FCRDI and RRDI. The Indian hybrid PHB71 (DP) showed a better and more consistent performance in both locations in both seasons, followed by the Sri Lankan hybrids. PHB71 (DP) matured earlier (93–95 days) than the Sri Lankan hybrids (115–125 days). All other varieties were inferior in all aspects except the earliness in 30006 (Ad), which matured within 85–87 days (Abeysekera et al 2003).

In the minor season of 2010, another set of Indian rice hybrids received through the Prima Company was tested at RRDI and results revealed that none of the Indian varieties performed better than the Sri Lankan hybrids except for their earliness in some varieties. All the Indian varieties had been infected by stem borer and as a result grain yield was poor (Table 3).

Agronomic management of hybrids. Success in commercial hybrid rice varieties primarily depends on their high yield potential. Yan (1988) observed that the growth pattern and nutrient requirement of hybrid rice differ considerably from those of inbred rice varieties and, therefore, to exploit this advantage of hybrid rice, it is necessary to adopt appropriate crop management practices. Most of the studies on optimizing hybrid rice yield were conducted with temperate hybrids in China and those strategies cannot be applied for tropical countries (Peng et al 1998). Therefore, the development of appropriate management practices for local conditions is very important. Extensive studies on aspects such as nursery management, transplanting spacing, establishment methods, nutrient management, etc., for locally developed hybrids have been conducted. To date, a broad agronomic package for the cultivation of hybrid rice has been developed. However, there is a need to fine-tune the package for each hybrid combination.

Effect of nursery seeding rates on the grain yield of hybrids. Experiments conducted using three RRDI hybrid rice varieties (BgHR1, BgHR6, and BgHR12) revealed that seedlings raised at 20–30 g/m nursery density performed better and produced higher yield (Jayawardena et al 2004).

Transplanting spacing per hill density and nitrogen responses. Nursery seedbed management, transplanting spacing, per hill plant density, and fertilizer management are more important for hybrid rice cultivation. Two separate experiments conducted at RRDI with two RRDI hybrids (BgHR6 and BgHR12) revealed that higher yield could be obtained by transplanting two seedlings per hill with wider spacing (20 × 25 cm, 25 × 25 cm), which is comparable with that of spacing (15 × 15 cm and 15 × 20 cm) recommended for inbred varieties (Jayawardena and Abeysekera 2002).

Nutrient management. A nitrogen fertilizer response study conducted with inbred and RRDI hybrids revealed that the response to nitrogen of inbreds and hybrids is similar and maximum yield response was observed up to 180 kg/ha N. The maximum yield obtained at 180 kg/ha N by hybrids and inbreds was 6.8 and 6.4 t/ha, respectively (Jayawardena and Abeysekera 2002). The fertilizer recommendation given for Bg407H was similar to that of inbred rice except for the application of an additional dose at flowering date. An experiment at RRDI revealed that the application of zinc and sulfur is required to obtain higher grain yield from Bg407H and application of magnesium is not required in low humic gley soils in the low-country intermediate zone (Bandara et al 2009).

Seedling broadcasting method as an alternative method for manual transplanting. In hybrid rice cultivation, transplanting is important to reduce the seed cost, as it is costlier than that of inbred rice. However, present-day Sri Lankan farmers are reluctant to transplant the crop due to the requirement of additional labor for transplanting. Studies conducted at RRDI and in farmers' fields revealed that seedling broadcasting (parachute method) could be adopted as an alternative method for manual transplanting. This would help to cut down the labor cost required for manual transplanting and seed requirement by around 50% (Jayawardena et al 2004). This method is now being practiced by farmers in many parts of the country. This method has potential for adoption in foundation seed production programs on government seed farms. Seedlings raised in the parachute nursery could be thrown into standing water up to

2.5-cm depth to control weeds without affecting yield (Hasalaka 2006). Dharmasena and Jayawardena et al (2005) reported that insecticide use to control thrips could be minimized using seedling broadcasting. Recent studies conducted at HARTI on farmer adoption of seedling broadcasting revealed that this method has a yield advantage of more than 25% over conventional methods (Renuka, pers. comm. 2009).

Direct-sown hybrid rice cultivation technology

A majority of Sri Lankan farmers adopt direct seeding in rice cultivation due to the additional labor cost incurred with transplanting and this is one of the problems in promoting hybrid rice. Recently, a seed paddy and labor-saving technique called seedling broadcasting/parachute method was introduced for hybrid rice cultivation as an alternative to manual transplanting (Jayawardena et al 2004). Increasing prices of seedling trays and difficulty in access to seedling trays are two problems associated with this system. Studies conducted at RRDI during 2007-09 revealed that direct seeding at a low seed rate (50–75 kg/ha) could be possible in hybrid rice cultivation compared with 100 kg/ha in direct seeding of inbred rice. Jayawardena and Abeysekera (2009) and Kahandawala (2010) also reported the possibility of adopting a low seed rate (15–30 kg/ha) for direct-sown Bg407H in the wet zone in combination with straw mulch application. Another study conducted with inbred and hybrid rice on weed emergence and growth patterns found higher weed biomass in the early stages in HR plots and suggested the importance of weed control in the early stages in hybrid rice (Abeysekera et al 2001).

Testing of combining ability with DNA analysis

Studies on general combining ability (GCA) that determines additive genetic effects and specific combining ability (SCA) for nonadditive genetic effects started. Restorers for additive effects for grain yield, number of spikelets, and length of panicles have been identified. DNA studies have indicated that some hybrids have a higher heterosis than parental lines. These methods cut down the time required to evaluate parental lines compared with conventional grow-out tests.

Seed production

The commercial viability of the hybrid rice industry depends on seed yield, economics, and efficiency of seed production in CMS lines and F_1 seed yield. Hybrid rice seed yield is influenced by many factors such as climate, synchronization of parental lines, and the outcrossing rate of CMS lines and special attributes such as panicle exsertion rate, etc. The seed production ability of different CMS lines in different locations was studied and the minor season was found to be the best season and intermediate zone (Girandurukotte) the best location for F_1 seed production (Kiriwaththuduwage et al 2002). Other than those factors, row transplanting of A and R lines to a specific row ratio, application of GA3, leaf clipping, and supplementary pollination are very important activates to obtain higher F_1 seed yield. Results of the experiments carried out at RRDI have revealed that a row ratio of 3 R:4–6 A is better than the IRRI recommended row ratio of 3 R:8–10 A (Abeysekera et al 2008). Applications of GA3 are essential for getting higher F_1 yield and the rate of application depends on the type of CMS lines and the environmental conditions prevailing at the seed production site. Application of GA3 at 120 g/ha was found to be the best under Sri Lankan conditions and the optimum dose of GA3 is 120 g/ha (Kiriwaththuduwage et al 2004). However, the cost of GA3 is higher than that of other cost components in F_1 seed production (Silva 2010) and therefore it should be applied correctly to get the maximum benefit.

Large-scale seed production

A study conducted by RRDI at different locations on a large scale found that hybrid rice showed a 21.6% (12.5–30.7%) yield increase over inbred varieties. The cost of cultivation of hybrid rice was estimated to be Rs. 65,900/ha (US$659/ha), which is a little higher than that of inbred rice cultivation under transplanted conditions (Rs. 62,962/ha; US$630/ha). F_1 seed yield was around 0.65 t/ha and the cost of cultivation estimated as Rs. 95,230/ha (US$630/ha), which is 1.7 times higher than that of inbred rice cultivation. Poor synchronization of parental lines was the major factor for low seed yield. The current cost of production of F_1 seed is Rs. 147/kg and this can be brought down substantially by increasing F_1 seed yield through the better synchronization of flowering of parental lines and by adopting-labor saving techniques in crop establishment (Jayawardena and Abeysekera et al 2006). Another study conducted by Silva (2010) indicated that the cost of production increased from Rs. 120/kg to Rs. 225/kg at RRDI and to Rs. 333/kg in farmers' fields and even with these prices it is still profitable to undertake hybrid rice cultivation. A small-scale seed production program was started in farmers' fields in Devehuwa and Rajanganaya in the minor season of 2008. The results were encouraging and therefore, during the minor season of 2008-09, a pilot-scale "Hybrid rice Saruketha yaya program" was started with collaboration from the extension and communication center of the DOA and financial support from the FAO/TCP. The objective of the program was to introduce a self seed production program to supply F_1 seed for the area. The program was conducted in 25 locations at Polonnaruwa, Rajanjanaya, Devahuwa, System B, and System C. Farmers were able to produce reasonable F_1 yield (100–200 kg/ha), except for system B and C. In the 2009-10 major season, a new site of F_1 seed production was started at RARDC, Makandura, and reasonable yield of around 250 kg/ha was obtained.

Other activities

With assistance from FAO/TCP, training programs for officers of the DOA and farmers who were willing to engage in hybrid rice seed production and cultivation were held at RRDI. Farmers were given seed materials and other necessary materials such as GA3 and polythene to separate the seed crop from other rice plots. RRDI officers periodically visited the farmers and gave them the necessary training and instructions. This experience indicated to us that F_1 seed production of rice hybrids is feasible; however, farmers' realizable F_1 yield was comparatively poor due to poor synchronization and inadequacy of artificial flowering. Some farmers sold their seeds at Rs. 400–500/kg (US$4–5). Establishment of a hybrid rice demonstration plot at Schools of Agriculture in Sri Lanka and the inclusion of hybrid rice technology as a subject matter in the curriculum for a diploma in agriculture are also planned. The IRRI-published hybrid rice seed production manual was translated into Sinhala and Tamil languages. A video CD on hybrid rice seed production was prepared for training purposes.

Problems related to hybrid rice research and development

There are many problems related to hybrid rice research and development and the most important ones follow:

1. Limited grain yield heterosis in experimental hybrids. This could be due to the narrow genetic diversity among available CMS sources and restorers. Priority should be given to developing CMS lines with a high outcrossing rate.
2. Low F_1 and CMS yield. This is mainly due to the low outcrossing rate of available CMS lines that are used to produce hybrids and poor management practices. Current F_1 and CMS management practices need to be refined and new methodology has to be developed for new varieties.
3. The lack of an isolated place/location for a hybrid rice research program, especially for breeding.
4. The lack of a rapid quality testing program for the F_1 seeds produced by both researchers and farmers.

Development needs

The following are important development needs:

1. Qualified scientific staff for the hybrid rice research program. Need additional qualified staff and resources to independently conduct activities.
2. Seed certification standards for hybrid rice.
3. More participation by the private sector in the hybrid rice seed industry. Favorable government policies and interventions are required for the establishment of a sustainable seed production program with the available physical and other resources. Hybrid seed could be produced on government seed production farms if special allocations were provided for this purpose.
4. The hybrid rice research program is carried out at RRDI, Batalagoda, side by side with the inbred program in which thousands of inbred lines are handled and also surrounded by farmers' rice fields. Therefore, it is very difficult to maintain the purity of genetic materials even with remedial measures. This could be overcome by establishing a separate but common hybrid research center/institute for all crops, including other crops.
5. F_1 seed production is currently handled by RRDI, but this is extremely difficult. Seed production could be undertaken by government seed farms or some other party. Since HR seed production is not a profitable venture, under the current situation, it's difficult to handle an F_1 seed program on seed farms unless they receive special funds and labor and other facilities. The private sector is also not interested in F_1 seed production because it is reluctant to invest. Favorable policies should be adopted such as testing of

imported and local hybrids. Seed production of selected hybrids should be done in Sri Lanka, for which appropriate incentives should be provided by the government.

Conclusions

During the last 30 years, RRDI has made significant achievements in hybrid rice research and development. RRDI was able to develop local CMS lines, maintainer lines, and restorers that could be the most important lines in hybrid rice development. Other than these lines, the development of two hybrid varieties (Bg407H, already recommended, and BgHR8, to be recommended) was also a good achievement. Other than varieties, F_1 seed production has been perfected and this technology has been passed on to farmers. During the last 30 years, RRDI has overcome several constraints and needs to be strengthened further. The DOA has to give priority to hybrid research and development programs. It is very important to set up a separate institute for hybrid technology in the country. The inadequacy of scientific staff and nonavailability of suitable separate land for seed production are two major problems that need to be solved immediately to obtain the expected benefits from the hybrid rice research and development program. The low outcrossing of currently available CMS lines needs to be improved and good restorers also need to be improved. The hybrid rice research and development program in Sri Lanka should be continued and expanded since remarkable progress has been made but more needs to be made.

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Notes

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Recent achievements in research and development of hybrid rice in Vietnam

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Hybrid rice research in Vietnam changed direction to the two-line system during 2005-10. Work was conducted intensively to exploit available developed TGMS lines for breeding two-line hybrids. To overcome some of the limitations of three-line hybrids, several varieties with short growth duration and available maintainer lines such as Jin 23B, BoB,II32B, and R58025B were crossed with TGMS lines. A set of TGMS lines having stability for male sterility, short growth duration, and a high rate of stigma exsertion have been developed. These newly developed TGMS lines showed stability for male sterility.The two-line hybrid approach used these TGMS lines as female parents and they outyielded the three-line hybrids. Additionally, several restorer lines (male parents) as well as TGMS lines with the wide compatibility gene have been developed. Several indica-japonica hybrids have been developed and super high yields of some hybrids were recorded in experimental fields. The new TGMS lines developed in Vietnam were used as female parents of released two-line hybrid varieties such as VL20, TH 3-3, TH3-4, HC1, HYT102, HYT103,HYT108, and HYT106 and some promising hybrids (HYT116, HYT117, and HYT119). Regarding quality aspects, hybrid rice developed in Vietnam has better eating quality than hybrids introduced from China. The F_1 seed production package for each released hybrid was developed by different research institutes. The average yield of F_1 seeds in Vietnam was 2.2−2.5t/ha. A total of 1,500–2,260 ha are used for hybrid seed production every year, producing 5,000–6,000 tons of hybrid rice seeds. Hybrid rice seed area has decreased in recent years because of damage caused by changing climate. However, for commercial rice production, hybrid rice has been planted on 600,000–700,000 ha per year in Vietnam, with an average yield of 7.0 t/ha for the spring season and 6.0 t/ha for the summer season.

Keywords: CMS, TGMS, hybrids, maintainer lines

Hybrid rice technology has been exploited in commercial rice production since 1992. Hybrid rice seed production technology as well as hybrid rice breeding work have been developed intensively since 1994. In the first step, Vietnam's hybrid rice development focused on seed production technology and testing introduced hybrids for expanded hybrid rice cultivation. Using parental lines developed originally from China and the International Rice Research Institute (IRRI), Vietnam successfully developed hybrid rice seed production technology. Later, Vietnam also developed its own hybrid rice varieties. Since 2000,Vietnam has conducted hybrid rice seed production on 1,500 to 2,000 ha per year, with yield of 2.0 t/ha. The advantages of hybrid rice have been confirmed by its high yield, short duration, and suitability for a late spring rice crop and early summer crop. However, hybrid rice still shows disadvantages in grain quality and susceptibility to diseases and insects. Furthermore, hybrid rice seed production in the northen provinces also faces several problems, especally damage caused by changing climate. All these constraints prevented an expansion of hybrid rice seed production as well as hybrid rice production in Vietnam.

In order to overcome the problems in hybrid rice development, Vietnam has intensively invested in improving hybrid rice varieties as well as in hybrid rice seed production technology. The achievements and progress of hybrid rice research and development are presented and discussed in thís chapter.

Recent achievements in hybrid rice research and development in Vietnam

Results from developing new tropical TGMS lines

To create new tropical TGMS lines adapted to tropical conditions, adapted cultivars were crossed to available TGMS lines and new TGMS lines were selected in segregating generations. The new TGMS lines had stable pollen sterility under a critical temperature of 23–24 ^{o}C, uniformity in phenotype, along with good combining ability and good flower characteristics, and they were selected and used for making new hybrid rice combinations. The new TGMS lines created by different research institutions are presented in Table 1.

Among newly developed TGMS lines, T1S-96 and 103S were used as females for released two-line hybrids VL20, TH3-3, TH3-4, and HC1, and other TGMS lines such as P5S, AMS30S, and TGMS1 were used as females for released hybridsHYT102, HYT103, HYT108, TH5-1, and LHD6 (Hoan 2007).

Developing new TGMS lines based on genotype of parental lines (maintainer lines and restorer lines of adapted three-line hybrids)

Maintainer lines for three-line hybrids such as II-32B, IR58025B, Jin23B, BoB, and Zhenshan97B and some restorers such as Fuhui838, 827R, and Gui99, etc., were characterized by short duration, short plant height, and good combining ability and they are adapted to Vietnamese conditions. These parental lines have been used for crossing with four TGMS lines (S, 7S, CN26S, and TG125S), and they were successively backcrossed to recurrent male parents to the BC_2F_1 and BC_3F_1 generation before selecting pure TGMS lines.

The first set of TGMS lines based on genotypes of maintainer lines was selected in the F_8BC_2 generation. These newly developed TGMS lines have genotypes as well as phenotypes similar to those of the correspondent CMS lines BoA, IR58025A, II32A, and Jin23A. For convenience in use, they were named, respectively, AMS 34S (BoS),

Table 1. Available TGMS lines developed and used in Vietnam during 2001-05.

Line	Source	Institution	Critical fully sterile temperature (°C)	Critical fertility temperature (°C)	Use
T1S-96,103S		HAU	25.5	22–23	Commercial
P5S	T1S ×	HAU	25, daylength 12h 16 min	≤24	For breeding
AMS27S(7S)	TGMS × Inbred	VASI	25	23.5	For breeding
AMS 28S(11S)	TGMS × Inbred	VASI	25	23.5	For breeding
AMS 29S(534S)	Selected from segregations	VASI	24.5	23	Promising variety
AMS 30S(827S)	Selected from segregations	VASI	24.5	23	Commercial use (HYT102, HYT103, HYT108)
AMS26S (CL64S)	Selected from PeiAi 64S	VASI	24.5	23	For breeding
AMS31S	CL64S × VN292-2	VASI	25.5	≤23	For breeding, promising variety
AMS33S	CL64S × BM9820-11	VASI	25.5	≤23	For breeding, promising variety
TGMS1	Crossing	FCRI	25	≤24	LHD6
TGMS20	Pollen culture, TGMS6/Xi23	FCRI	25	≤24	For breeding
D101S	VN1 × DT12	AGI	>24	≤24	For breeding
D102S	VN1 × DT12	AGI	>24	≤24	For breeding
D103S	VN1 × DT12	AGI	>24	≤24	For breeding
TGMS18-2	H84 × CR203	AGI	>24	<24	For breeding
TG1	103S/S	Vanlam			For breeding
TG22	TGMS2/R15	Vanlam			For breeding

Table 2. Pollen sterility of newly developed TGMS lines observed in the summer season.

TGMS lines	Original cross	Pollen sterility (%)	Type of pollen sterility	Average temperature (°C)
AMS34S(BoS)	TG125S/BoB	100	WA	27.6–30.8
AMS35S-1(255-1)	TG125S/25B	100	No pollen	26.2–30.8
AMS35S-2 (25S-2)	TG125S/25B	99–100	WA	26.2–30.8
AMS36S -1 (II32S-1)	7S/II32B	100	WA	26.2–30.8
AMS37S (Jin 23S)	7S/Jin23B	100	WA	26.2–30.8
AMS36S (II32S-2)	CN26S/II32B	98–100	WA	26.2–30.8

Table 3. Major characteristics of newly developed TGMS lines in the summer of 2008.

Character	AMS35S-1 (25S-1)	AMS35S-2 (25S-2)	AMS36S-1 (II32S-1)	AMS30S (827S)	AMS34S-10 (BoS-10)	AMS34S-11 (BoS-11S)	AMS37S-76 (JinS)	25A
Days to 10% heading	78	75	72	78	68	70	72	80
Stigma exsertion (%)	60	60	75	70	78	70	68	45
Stigma color	White	Black	Black	White	Black	Black	Black	White
Leaf number	15	14	15	14	12	12	13	14
Panicles/hill	6.4	6.4	5.0	5.4	90	9.4	7.4	8.7
Off-type plant (%)	0	0	0.5	0	0	0.1	0	0
Outcrossing rate (%)	47.2	49.7	51.7	45.6	53.8	51.3	47.9	37.6
Plant height (cm)	66.3	68.7	92.0	92.3	71.0	66.7	83.7	85.0
Sterile pollen (%)	100	100	90	100	100	100	100	100

AMS35S (25S), AMS36S (II32S), and AMS37S (Jin23S). The pollen and growth characters of these TGMS lines appear in Tables 2 and 3.

To show the advantages of newly developed TGMS lines based on available CMS lines, the correspondent restorer lines RTQ5, R100, and PM3 of existing three-line hybrids HYT83, HYT100, and HYT92, respectively, were used to cross with 25S, a newly developed TGMS line similar to IR58025A. In fact, IR58025A is the female parent of three-line hybrids: HYT83, HYT100, and HYT92. Comparing yield components and the yield of two-line and three-line hybrids having a similar genotype showed that two-line hybrids had more spikelets per panicle and lower spiklet sterility than their three-line hybrids; therefore, they have higher yield than three-line hybrids (Table 4).

Results of test crosses confirmed that new TGMS lines based on maintainer lines of three-line hybrids have been successfully developed. These results have opened up opportunities to replace three-line hybrids with two-line hybrids to overcome limitations such as instability of pollen sterility of II-32A and medium exsertion of IR58025A in Vietnam. In addition, new TGMS lines based on B lines require no restorer genes in the male parents; therefore, more opportunities exist to breed two-line hybrids with high heterosis than with existing three-line hybrids.

Results of the development of parental lines having the WC gene

Conventional high-yielding varieties adapted to Vietnamese conditions are ones such as Xi23, Q5, Chiem77, R242, BM9855, etc. These varieties were used as male parents to cross with donors having the WC gene such as PeiAi 64S, N22, Palawan, Dular, Calotoc, Lambayeque1, and Moroberekan. Single crosses were made and selection for parental lines followed two directions:

(i) Fertile plants were selected in segregating generations to develop male parents having the WC gene.

(ii) Sterile plants were selected in segregating generations of single crosses or in backcrossing generations. Sterile plants in the F_6BC_1 generation were used to testcross to an indica/japonica check to identify a female parent having the WC gene in the spring and summer of 2005. A total of eight uniform TGMS lines having 100% pollen sterility were selected. These selected TGMS lines having good stigma exsertion, short duration, and phenotypic acceptability

Table 4. Yield components observed in newly developed two-line hybrids compared with their original three-line hybrids

Type of hybrid	Panicles/ hill	Spikelets/ panicle	Spikelet sterility (%)	1,000-grain weight(g)	Weight of 5 plants (g)
HYT100 (2-line)	7.2	219.3	8.4	28.6	159.0
HYT100 (3-line)	6.0	170.0	21.0	28.0	101.0
HYT83 (2-line)	6.4	239.3	11.3	22.2	122.0
HYT83 (3-line)	6.6	185.3	19.4	23.3	99.3
HYT92 (2-line)	7.4	244.3	9.6	24.8	160.0
HYT92 (3-line)	6.0	206.0	18.4	24.6	110.0

are good as female parents for developing two-line hybrids. Those selected TGMS lines have been crossed to an indica/japonica check. Results showed that TGMS lines named D59S, D60S, D64S, and D66 have the WC gene (Table 5).

Molecular markers were used for breeding parental lines having the WC gene and restorer gene. Using S in this study, we identified an S5 gene linked to markers RM253, RM225, RM136, and RM418. These markers have been used to identify segregating plants having the WC gene in parental breeding programs. Similarly, markers RM258 and RM315 have been used for selecting lines having the *Rf* gene.

With the *tms* gene to select TGMS lines, a total of 37 primers were used to identify a marker for the *tms* gene in a cross of CL64S × R242, and two SSR markers (RM5862 and RM5897) were identified to link to the *tms* gene in CL64S.

Developing TGMS lines through anther culture of F_1 of crosses (TGMS lines × inbred varieties)

Anther culture was used to develop TGMS lines from crosses between TGMS lines and inbred varieties (including maintainer lines of the three-line hybrids). Anther culture of the F_1 generation of 18 hybrids was used. A lot of TGMS lines with stable pollen sterility were isolated. However, only six TGMS lines having good growth characteristics such as short duration, 100% pollen sterility, and good stigma exsertion were selected for use in breeding programs of Vietnam (Table 6). Through the anther culture method, new TGMS lines could be developed in 2 years compared with the 4 to 5 years using the pedigree selection method (Nhan 2005, Hoan 2005).

Results of developing new maintainer lines for developing CMS lines

Seventeen good maintainer lines with short duration, short stature, good adaptation to Vietnamese condition, tolerance of diseases, and good combining ability were selected from a testcross nursery for developing new CMS lines. Completely male sterile plants were selected for backcrossing to their corresponding CMS lines.

The backcrossing populations were in different states. Among 12 crosses were selected 3 completely sterile CMS lines that were developed and named OM1-2A, AMS 71A, and AMS 72A. These new CMS lines have been used for testcrossing in the hybrid rice breeding program.

In order to diversify and improve mantainer lines for use in three-line hybrid rice breeding, seven available maintainer lines were crossed in pairs to develop new maintainer lines having short duration, good phenotype, good tillering, high stigma exsertion, and improved quality of CMS lines. Six crosses involving eight maintainer lines as their parents were selected following the bulk method. In the F_4 generation, 20 to 25 individual plants were selected for backcrossing in pairs with corresponding individual plants of eachCMS line.

From the F_5 generation, 132 promising lines were selected and 38 lines were crossed in pairs again with the corresponding CMS lines, with the 24 lines showing themselves to be good maintainers for pollen sterility of CMS (WA source). Back-crossing was continued to convert these promising maintainer lines to new CMS lines (Table 7).

Table 5. Characteristics of TGMS lines expected to have the WC gene selected from single crosses involving female parents with the WC gene.[a]

TGMS line	Original cross	Plant height (cm)	Days to flowering (days)	Critical temperature for male sterility (°C)	Sterile pollen (%)	Stigma exsertion (%)	Phenotype acceptability (score)	Spikelet/ panicle	Seedset of F_1 testcrossed with indica and japonica
D52S	CL64S/Q5	75.9	62	24	100	65	3	150	
D59S	7S/Lemon	80.2	64	24	100	75	3	158	>90, > 85
D60S	CL64S/Chiem77	78.9	62	24	100	65	3	165	>80, >70
D64S	7S//7S/W3	75.5	62	24	100	70	3	178	>60, > 55
D66S	CL64S//T1S-6/GR564	79.2	64	24	100	70	3	175	>75, >75
D67S	CL64S/GR272/Xi12	78.3	62	24	100	70	3	165	>75, >85
D68S	CL54S//C70/CR203	82.3	64	24	100	70	3	165	
D116S	CL64S/IR23030/ /IR23030	78.2	64	24	100	75	3	162	
D161s	CL64S/IR23030//IR23030	78.2	62			70	3		
CL64S	From China	78.0	70	24	95.0	70	3	155	

[a]All lines had a phenotype acceptability score of 3, on a scale of 1–5, where 1 = unacceptable and 5 = acceptable.

Table 6. Major characteristics of new TGMS lines developed through anther culture of F_1 plants.

TGMS line	Cross	Institution where developed	Days from seeding to flowering	Sterile pollen at >24 °C (%)	Stigma exsertion	Stigma color
CNSH8S	PeiAi64S/25B	VASI	62 (M)	100	Good	White
CNSH9S	PeiAi64S/25B	VASI	65 (M)	100	Good	White
TGMS H7	PeiAi64S/ZS97B	FCRI	65 (M)	100	Good	White
TGMS H20	PeiAi64S/Xi23	FCRI	82(x)	100	Good	White
TGMS CN1	TGMSVN7/inbred	AGI	73(x)	100	Good	Black
TGMS CN2	TGMSVN7/inbred	AGI	68 (M)	100	Good	Black
PeiAi64S	Introduction	China	62 (M)	91.5	Good	Black

Table 7. Major characteristics of developed CMS lines.

Name	Parent	Growth duration (days)	Plant height (cm)	Panicles/ hill	Sterile pollen (%)	Stigma exsertion (%)	Grain shape
248	D62A/R623 (BC7)	65	75.2	10.2	98.8	70–75	Long
135	BOA/BK25 (BC5)	71	62.4	10.8	90.0	50–55	Bold
157	25A/B831 (BC6)	71	87.6	11.6	90.0	75–80	Long
8	BOA/BK1-5-1 (BC7)	67	73.2	10.3	97.0	75–80	Long
279	II32A/OM2502-139 (BC9)	75	81.6	10.2	98.5	75–80	Long
211	IA/BK7-8-2 (BC7)	74	76.3	8.9	97.0	70–75	Bold
Check	BoA	65	66.2	8.2	99.0	70–75	Bold

Results of developing new hybrid rice combinations for commercial hybrid rice production

Twelve stable male sterile CMS lines, 10 TGMS lines, and 2,000 male parents (inbred lines and varieties) were used in testcrossing to develop two-line and three-line hybrids for Vietnam. A total of 481 rice hybrids were evaluated in observation yield trials and 134 promising hybrids were selected for primary yield trials and 15 to 18 promising hybrids were selected per year and were tested in the National Hybrid Rice Yield Trial (NHYT). The NHYT was conducted in different ecological conditions (6–9 locations).

Promising two-line hybrids were identified in national multilocation yield trials and the program of national testing of MARD and these appear in Tables 8, 9, and 10 (Hoan 2009).

For quality aspects, a study on milling percentage, heading percentage, length of grain, length/width ratio, amylose content, etc., showed that these characteristics of hybrid rice are similar to those of inbred checks. However, the amylose content of hybrid rice is lower (18–20%). For eating quality, hybrids HYT100 and HYT92 were evaluated as having very good quality with an aromatic aroma. HYT83 and TH3-3 were evaluated as having good eating quality with high yield potential (Table 11).

The high-yielding hybrids with wide adaptability, good quality, and tolerance of diseases and insects were selected and released for commercial rice production (Table

Table 8. Average yield of selected promising combinations in the National Hybrid Rice Yield Trial (6–9 locations).

Season	Hybrid	Average	Type of hybrid	Duration (days)	Remarks
Spring 2006	HYT 102	6,210	2 line	125	
	HYT 103	6,460	2 line	124	Good quality
	HYT 106	6,150	2 line	126	
	HYT 107	6,260	2 line	128	
	HYT 105	6,260	3 line	128	
	Eryou 838 (check)	6,200	3 line	130	
Spring 2007	HYT 102	7,400	2 line	125	
	HYT 103	7,400	2 line	125	Good quality
	HYT 106	7,700	2 line	126	
	HYT107	7,500	2 line	128	
	Eryou 838 (check)	6,270	3 line	130	
Spring 2008	HYT 106	7,381	2 line	126	
	HYT 115	7,533	2 line	128	
	HYT 116	7,434	2 line	130	
	SL 8H (Agri Tech.)	7,588	3 line	135	Good quality
	HYT 92	7,077	2 line	135	Good quality
	II32S/MK 63	7,091	2 line	135	
	33S/PM3	7,530	2 line	135	
	Eryou 838 (check)	6,914	3 line	130	
Spring 2009	HYT 115	7,250	2 line	135	
	HYT 106	7,320	2 line	126	
	HYT 119	6,820	2 line	135	
	AMS30S/R128	7,420	2 line	136	
	Eryou 838-(check)	7,050	3 line	139	
Spring 2010	HYT122 (AMS30S/R725)	7140	2 line	129	
	HYT123 (AMS30S/R8-1)	7110	2 line	123	
	HYT100	7190	2 line	128	Good quality
	Eryou 838	7140	3 line	123	Chinese hybrid
	Dyou527	6850	3 line	130	Chinese hybrid

Table 9. Average yield of high-quality hybrid rice HYT100 and HYT83 in the spring season of 2003-05.

Hybrid	National Hybrid Rice Yield Trial						National testing		Average yield (t/ha)
	Spring 2003		Spring 2004		Spring 2005		Spring 2004		
	No. of provinces	Yield (t/ha)	No. of provinces	Yield (t/ha)	No. of provinces	Yield (t/ha)	No. of provinces	Yield (t/ha)	
HYT100	6	6.84	7	7.45	7	6.76	8	6.56	6.89
Eryou838 (check)	7	6.50	6	6.99	7	6.63	8	6.52	6.64
HYT83	7	6.75	8	7.71	–		–	–	7.26

Table 10. The results of demonstrations in Hai Duong Province, spring 2004.

Variety	Binh Xuyen-Binh Giang-Hai Duong		Hop Tien-Nam Sach-Hai Duong		Average yield (kg/ha)
	Area (m^2)	Yield (kg/ha)	Area (m^2)	Yield (kg/ha)	
HYT83	15,210	8,520	1,500	8,440	8,480
HYT100	526	7,837	500	7,780	7,809
D.yo¬u 527	1,721	8,113	1,500	8,390	8,252
Eryou. 838	5,476	7,902	5,000	7,580	7,741
CV1	1,051	7,425	1,000	7,620	7,523
Khang dan 18 (Check)	900	7,182	1,000	6,920	7,051
Q5 (Check)	900	7,695	1,000	5,810	6,752
Boi tap son thanh	2,297	7,224	2,000	7,000	7,112

Table 11. Good rice hybrids develped during 2000-10 by FCRI.

Hybrid	Type of hybrid	Yield (kg/ha)	Status	Developer
HYT83	3 line	7,000–9,000	Released	
HYT92	3 line	6,500–8,000	Released	
HYT 100	3 line	7,000–9,000	Released	Hai phong seed company
HYT 102	2 line	6,500–8,000	Released	Hai duong seed company
HYT103	2 line	6,500–8,000	Released	Dai duong seed company
SL 8H (Agri tech.)	3 line	7,000–9,000	Released	Đai thanh copany
HYT 108	2 line	7,000–9,000	Released	
LHD6	2 line	6,500–8,500	Released	
HYT 106	2 line	6,500–8,000	Ready for release	
HYT 109	2 line	6,500–9,000	Promising	
HYT116	2 line	7,000–9,000	Promising	
HYT117	2 line	6,500–8,500	Promising	
HYT118	2 line	6,500–8,500	Promising	
HYT115	2 line	6,500–8,500	Promising	
HYT119	2 line	6,500–8,000	Promising	

12).The released hybrids were HYT83, HYT92, HYT100, and SL8H (three-line hybrids) and VL20, TH3-3, TH3-4,HC1, HYT102, HYT103, and HYT10 (two-line hybrids). Several promising two-line hybrids such as VL1, HYT106, HYT107, and TH3-5 and three-line hybrid HYT105 have been identified for farmer field demonstrations (Tram 2005).

Two-line hybrids developed in Vietnam have several advantages. They are of short duration and are suitable for the late spring and early and very early summer rice crop, although most existing three-line hybrids are not adapted to the early summer

Table 12. Area and productivity of hybrid rice commercial production in Vietnam during 2000-11.

Year	For year		Spring crop		Summer crop	
	Area (ha)	Yield (t/ha)	Area (ha)	Yield (t/ha)	Area (ha)	Yield (t/ha)
2000	435,508	6.45	227,615	6.50	207,893	6.37
2001	480,000	6.44	300,000	6.60	180,000	6.30
2002	500,000	6.30	300,000	6.50	200,000	6.00
2003	600,000	6.30	350,000	6.45	250,000	6.00
2004	577,000	6.04	350,000	6.45	277,000	5.40
2005	660,000	6.81	350,000	6.40	252,000	5.36
2006	584,200	6.32	346,000	6.50	238,000	6.15
2007	610,000	6.72	390,000	6.80	230,000	6.30
2008	581,361	6.80	326,384	–	254,977	–
2009	709,270	6.50	404,160	6.73	305,110	5.70
2010	605,642	6.85	374,342	6.85	231,200	6.00
2011	595,000	6.70	395,190	7.00	200,000	6.20

Source: MARD (2012).

rice crop. In addition, hybrid seed production of two-line hybrids reaches 2.5–3.0 t/ha but is only 1.5–2.0 t/ha for three-line hybrids (HYT83, HYT100, HYT92).

Studies on disease and insect resistance

The best restorer lines such as Ce64, Gui99, RTQ5, R242, 827R, Minghui63, R253, etc., have been used as female parents to cross with IRBB4, IRBB5, IRBB7, and IRBB21, and the F_1s were successively backcrossed with the corresponding restorer. The new restorer lines with bacterial blight resistance genes *Xa4*, *xa5*, *xa7*, and *Xa21* have been developed for use in hybrid rice breeding in Vietnam. Restorer lines having *Xa21* have been used as pollen parental lines of VL24 (a two-line hybrid) and Nanyou 2 (a three-line hybrid). These hybrids showed moderate resistance to bacterial leaf blight in northern Vietnam. However, when more than 120 kg of nitrogen are applied per ha, VL24 is susceptible to bacterial leaf blight.

Using the *Xa4* gene in hybrid rice breeding, sequence-tagged site (STS) markers MP1 and MP2 located on chromosome 11 were reported by Yoshimura. We used these markers in our study. The ADN of 137 plants of the F_2 generaton of the cross IR24 × IRBB4 was analyzed after conducting PCR by using primers of STS MP1 and MP2. The results showed that 33 plants had the *Xa4* (RR) gene, 66 plants had *Xa4* (Rr), and 38 plants had *Xa4* (rr). Results of artificial inoculation of race 2a giving phenotypic symptoms were confirmed with gene *Xa4* identified by STS markers MP1 and MP2.

Gene *Xa7* was identified for tolerance of almost all races of bacteria causing BLB in the northern provinces of Vietnam. The STS markers P3, M3, and M5 located on chromosome 6 were reported to link to the *Xa7* gene. However, in our study, we used marker P3 among 160 F_2 plants of the cross of IRBB7 with IR24. The results of PCR showed that 41 plants had the *Xa7* (RR) gene, 47 plants had *Xa7* (rr), and 72 plants had *Xa7* (Rr).

We currently use STS marker P3 to select and generate plants having the*Xa7* gene in our breeding program.

The *Xa21* and *xa5* genes were confirmed to have resistance to bacterial races of the northern provinces of Vietnam. In our study, we used STS markers pTA 818 and pTA248 on chromosome 11 for the *Xa21* gene and STS marker RG556 and restriction enzyme Dral to cut PCR product (Nhi et al 2009).

In order to develop TGMS lines with resistance to BLB, a set of good TGMS lines has been crossed with different donors. The selection for BLB resistance genes has been facilitated by molecular marker selection.

Published documents showed that several markers are used for breeding brown planthopper (BPH) resistance (Table 13). After screening, we confirmed SSR markers RM1767, RM6005, RM7187, and RM3367 with links to the Bphz gene.This gene is located in lines E1, E2, E3, E7, and E8. These lines were used as donors for developing parental lines having the Bphz gene.

Hybrid rice seed production in Vietnam

The area for hybrid seed production in Vietnam has been relatively stable in recent years (Table 14) for the following reasons:

- The subsidized support fund from the government declined (US$250/ha) to about 10% of seed production cost per ha, while the cost of labor, chemicals, and fertilizer increased.
- The yield of F_1 seed production has been unstable because of changing climate: too hot or too cold at the flowering stage of parental lines. The low yield of seed production led to lower benefits for seed growers.
- The system of cooperatives independently conducting F_1 seed production led to difficulties in selling and distributing F_1 seeds as goods in commercial markets.

The followings aspects are parts of the new approach for hybrid seed production in Vietnam:

- Private or joint-stock foreign seed companies, purchased breeder rights, and exclusive rights to produce F_1 hybrid and sell the hybrid rice seed. The hybrids VL20, TH3-3, TH3-4, HYT103, and HYT100 have been purchased by five seed companies: four Vietnamese seed companies and one Chinese seed company (DaiDuong seed company).
- The Ministry of Agriculture and Rural Development set a policy to support every seed company to carry out seed production on an area of more than 100 ha. The support included a $500/ha subsidy and funding for developing equipment and training, etc.

Results of seed production in Quang Nam and Daklak showed the following (Table 15):

For crosses of HYT83, HYT92, HYT102, and HYT106,the flowering of two parents was synchronized and therefore the yield of F_1 seeds was high: F_1 seed of HYT83 and HYT92 yielded from 3.0 to 3.5 t/ha, whereas in the northern provinces F_1 seed yielded only 1.2 to 1.5 t/ha.

Table 13. List of BPH-resistant hybrids identified in spring 2009.

Rice hybrid	Score[a]	Level of resistance[b]
HYT102	3	MR
HYT108	5	MS
LHD6	3	MR
827S/RTC	3	MR
827S/R544	3	MR
25S-51/GR10	3	MR
25S-49/BB4-Q99	4	MR
HYT106	6	S
SKCN3	3	MR
SKCN8	2	HR
5QSCNSH	3	MR
6QSCNSH	3	MR
9QSCNSH	3	MR
TN1	9	HS
Swanata	2	HR

[a]On a scale of 1 to 9, where 1 = highly resistant and 9 = highly susceptible.
[b]MR = moderately resistant, HR = highly resistant, S = susceptible, HS = highly susceptible.

Table 14. Area and productivity of hybrid rice seed production in Vietnam.

Year	Area (ha)	Yield (kg/ha)	Production (tons)
2000	620	2,300	1,426
2001	1,450	1,700	2,400
2002	1,600	2,400	3,840
2003	1,700	2,050	3,485
2004	1,500	2,150	3,225
2005	1,500	2,100	3,150
2006	1,915	2,020	3,866
2007	1,900	2,000	3,800
2008	1,000	2,200	2,640
2009	1,250	2,500	3,812
2010	2,200	2,700	5,940
2011	2,260	2,200	4,972

Source: MARD (2008).

Table 15. Results of hybrid rice seed production in Daklak Province, spring 2010

Hybrid	Parent	Date of seeding	Date of flowering	Growth duration (days)	Yield (kg/ha)	Remarks
HYT83	R1	30 Jan.	2 Apr.	87	3,000	Flooding after seeding
	25A		2 Apr.	91		
HYT92	R1	26 Jan.	7 Apr.	96	2,500	
	25A		8 Apr.	90		
HYT100	R1	28 Jan.	3 Apr.	88	1,500	None synchronized in flowering
	25A		30 Mar.	88		
HYT102	R1	23 Feb.	17 Apr.	78	2,000	Land used after seedling nursery
	AMS30S		16 Apr.	68		
HYT103	R1	23 Feb.	25 Apr.	86	1,700- 3,000	
	AMS30S		22 Apr.	74		
HYT106	R1	23 Feb.	18 Apr.	79	3,000	Land used after seeding
	AMS30S		17 Apr.	69		
HYT108	R1	23 Feb.	18 Apr.	79	3,000	Flooding after seeding
	AMS30S		22 Apr.	74		

F_1 seed yields of HYT102 and HYT106 were low due to the land used for seed production. It had poor fertility, resulting in female plants having only 70–100 spikelets/panicle.

The remaining hybrids (HYT100, HYT103, and HYT108) had unsynchronized flowering time of their parents, leading to low F_1 seed yield.

The results of hybrid rice seed production in Daklak (3,000–5,300 kg/ha for different hybrids) in the past 5 years have been considered as a turning point for hybrid rice seed production in Vietnam. Having a large plains land area and favorable climatic conditions for seed production, Daklak as well as Tay Nguyen have been chosen as bases for Vietnamese hybrid rice seed production in the coming years.

Issues identified for future research on and development of hybrid rice technology

The following issues have been identified for future research on and development of hybrid rice technology:

- The lack of hybrid rice combinations with good grain quality, tolerance of pests and diseases, and short duration (105–115 days) that meet the requirements of the various agroecological zones of the country.
- Appropriate genetic materials are needed to develop hybrid rice suited to southern Vietnam and with resistance to pests and diseases during the summer crop in the north.

Currently, hybrids are blast resistant but susceptible to major diseases such as bacterial leaf blight and sheath blight. Hence, they perform well only in the spring season due to lower disease pressure.

- No suitable conditions for hybrid rice seed production exist in the north, where hybrid rice is mostly cultivated to date, because of erratic climate and late harvesting time. Hence, there is a need to develop alternative seed production sites, such as Daklak (Tay Nguyen), Quang Nam, etc.
- A strong local seed production system involving both the public and private sector is lacking.
- Small farmers are reluctant to locally produce hybrid rice seeds due to greater risk; the very high financial requirement; the lack or proper warehouses, space, and cold storage for unsold seed; unavailability of pure CMS lines; and farmers' preference for imported seeds.

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Progress in breeding of super hybrid rice

Yuan Longping

In order to meet food requirement for all Chinese people in the 21st century, a super rice breeding program was set up by China' s Ministry of Agriculture in 1996. It was divided into three phases, with yield targets of 10.5/ha for phase I (1996-2000), 12/ha for phase II (2001-05), and 13.5/ha for phase III (2006-15) for average yield at two locations with 6.7 ha each in 2 consecutive years.

Through morphological improvement plus the use of intersubspecific (indica/japonica) heterosis, very good results have been achieved in developing super hybrid rice varieties.

Several pioneer super hybrids had been developed by 2000, which met the phase I yield standard and were released for commercial production starting in 2001. In recent years, the area under these pioneer super hybrids has been around 2 million ha and the average yield about 8.3 t/ha.

The breeding of phase II super hybrids was successful in 2004. The planting area of these hybrids reached 600,000 ha in 2011 and the average yield surpassed 9 t/ha.

Excitingly, a super hybrid variety, Y Liangyou No. 2, yielded 13.9 t/ha on average at a 7.2 ha demonstration location in 2012. This means that the goal of the phase III super rice breeding program was attained.

Technical approaches

Crop improvement practices have indicated, up to now, that there are only two effective ways to increase the yield potential of crops through plant breeding: morphological improvement and the use of heterosis. However, the potential is very limited when using morphological improvement alone and heterosis breeding will produce undesirable results if it is not combined with morphological improvement. Any other breeding approaches and methods, including high technology such as genetic engineering, must incorporate good morphological characters and strong heterosis; otherwise, there will be no actual contributions to a yield increase. On the other hand, further development of plant breeding for a super yield target must rely on progress in biotechnology.

Morphological improvement

A good plant type is the foundation for super high yield. Since Dr. Donald proposed the concept of ideotype in 1968, many rice breeders pay great attention to this idea and propose various models for super high-yielding rice. Among them, a well-known one is the ''new plant type'' proposed by Dr. Khush at the International Rice Research Institute (IRRI). Its main features are (1) large panicles, with 250 spikelets per panicle; (2) fewer tillers, 3–4 productive tillers per plant; and (3) a short and sturdy culm. Whether these models can obtain super high yield or not has yet to be proved.

Based on our studies, especially inspired by the striking characteristics of the high-yielding combination P64S/E32, which obtained a record yield of 17.1 t/ha, we found that super high-yielding rice variety has the following morphological features:

1. Tall erect-leaf canopy

The upper three leaf blades should be long, erect, narrow, V-shaped, and thick. Long and erect leaves have a larger leaf area, can accept light on both sides, and will not shade each other. Therefore, light is used more efficiently and air movement is also better within such a canopy. Narrow leaves occupy a relatively small space and thus allow a higher effective leaf area index. A V-shape makes the leaf blade stiffer so that it is not prone to be droopy. Thick leaves have a higher photosynthetic function and are not easily senescent. These morphological features signify a large source of assimilates that are essential to super high yield.

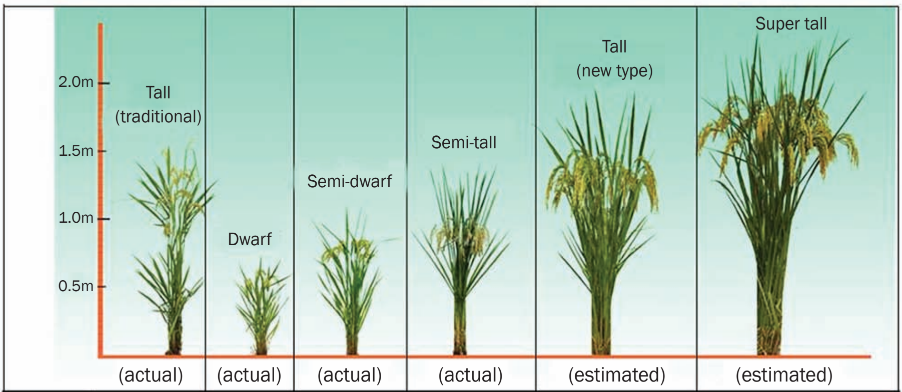
2. Lower panicle position

The tip of the panicle is only 60–70 cm above the ground during the ripening stage. Because the plant's center of gravity is quite low, this architecture enables the plant to be highly resistant to lodging. Lodging resistance is also one of the essential characters required for breeding a super high-yielding rice variety.

3. Larger panicle size

Grain weight per panicle is around 6 g and the number of panicles is about 250/m^2. Theoretically, the yield potential is 15 t/ha in this case.

Grain yield = biomass × harvest index. Nowadays, the harvest index (HI) is very high (above 0.5). A further raising of the rice yield ceiling should rely on increasing biomass because further improvement of the HI is limited. From the viewpoint of morphology, to increase plant height is an effective and feasible way to increase biomass. Our practice in breeding super hybrid rice has indicated a general trend, that is, the higher the plant height, the higher the biomass and grain yield, if only the HI remains at about 0.5 and the plant is resistant to lodging. This trend can be described in Figure 1.



HI	Approx 0.3	0.5	0.5	0.5	0.5	0.5
Yield	3–4 t/ha	6 t/ha	8–10 t/ha	12–14 t/ha	15–16 t/ha	>18 t/ha

Fig. 1. Trend of plant height to develop super high-yielding hybrid rice.

Increasing heterosis

According to our studies, heterosis in rice has the following general trend: indica/japonica＞indica/javanica＞japonica/javanica＞indica/indica＞japonica/japonica. Indica/japonica hybrids possess a very large sink and rich source, whose yield potential is 30% higher than that of intervarietal indica hybrids being used commercially. Therefore, efforts have focused on using indica/japonica heterosis to develop super hybrid rice. However, many problems exist in indica/japonica hybrids, especially their very low seed set, which must be solved to practically use their heterosis (Table 1). Making use of the wide compatibility (WC) gene（S_{-5}^{n}）and adopting an intermediate type instead of a typical indica or japonica variety as a parental line, several intersubspecific hybrid varieties with stronger heterosis and normal seed setting have been successfully developed.

Table 1. Yield potential of an indica/japonica hybrid.

Combination	Plant height (cm)	Number of spikelets/ panicle	Number of spikelets/plant	Seed setting rate (%)	Actual yield (kg/ha)
Chengte232 (japonica) ×26Zhaizao (indica)	120	269.4	1,779.4	54.0	8,250
Weiyou35 (indica/indica)	89	102.6	800.3	92.9	8,625
Increase (%)	34.8	162.8	122.4	–41.9	–4.3

Conclusions

Rice still has great yield potential. Based on the above progress, I have proposed the phase IV super hybrid rice breeding program, with a yield target of 15 t/ha and to be fulfilled by 2015.

I believe that the Chinese people can not only meet their food requirement by themselves, but they can also help other developing countries to solve their food shortage problems. Super hybrid rice can make a great contribution to world food security and peace!

Notes

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Progress in hybrid rice research and development in China

Luo Ju, Cao Liyong, and Cheng Shihua

Chinese scientists started research on male sterility in rice in the 1960s. The discovery of wild-abortive (WA) type cytoplasmic male sterile (CMS) lines in 1973 in Hainan was a landmark in China's second Green Revolution in rice. Since 1976, the commercial development of hybrid rice has made a great contribution to rice production in China. It was estimated that hybrid rice had been planted on about 480 million hectares, with an increase of nearly 550 million tons of rice during 1976-2010. With strong support from the government and seed companies, China has made great progress in hybrid rice R&D: (1) diverse CMS resources with elite traits have been exploited and used in hybrid breeding programs besides WA-CMS resources, which enhanced the genetic background of hybrid rice; (2) molecular marker-assisted selection for subspecies differentiation, disease resistance, and root system selection was performed in super hybrid rice breeding; and (3) their cool-water irrigation system has been adopted to solve the instability of male sterility in TGMS lines and some new TGMS lines with low critical temperature of fertility transformation have been developed in order to accelerate the large-scale production of two-line hybrid rice. The maximum yield for super hybrid rice reached 14.2 t/ha in 2011. The key points of future R&D for China's hybrid rice are also discussed.

Keywords: hybrid rice, male sterility, marker-assisted selection, super rice

Rice (*Oryza sativa* L.) is one of the most important crops in the world. It is a staple food crop for at least 65% of China's population. The performance of the rice sector in production and yield had been very impressive in most of the last six decades. The wide adoption of semidwarf varieties helped rice yield increase from 2 t/ha in the 1960s to 3.5 t/ha in the 1970s. However, the increase in rice production due to the development of semidwarf varieties failed to match the rapid increase in population. The exploitation of heterosis in rice became the most important choice for obtaining more rice (Cheng et al 2007). Since 1949, when the Peoples' Republic of China was founded, rice production continued to increase along with the Chinese population. China's total population reached 1.37 billion in 2011, an increase of 148.5% vis-à-vis the population in 1949. Meanwhile, rice yield per unit and total output had increased by 254.0% and 313.2% to 6.69 t/ha and 200.8 million tons, respectively, in 2011. However, rice sowing area increased by only 11.7% during this period and it had increased by only 30.0 million ha by 2011. Hybrid rice played an important role in the demand for food in China.

Prof. Yuan began research on heterosis in rice in 1964 (Yuan 1987). He found a natural male sterile mutant plant in indica rice, but couldn't find a restorer line. Fortunately, Li (1970) found pollen abortive materials in the natural population of wild rice (*O. rufipogon)*, which was the donor of cytoplasmic male sterility (CMS) for developing CMS lines. The development of the first CMS line in China in 1973 made it possible to exploit the heterosis of hybrid rice for commercial use. Then, the CMS system became successful for the exploitation of heterosis in rice although it is cumbersome as it involves three lines (CMS, maintainers, and restorers). Its use is also restricted to germplasm whose maintainers and restorers are not abundant (Cheng et al 2004). Shi Ming Song first reported that Nongken 58S, a male sterile mutant from japonica variety Nongken58, was a photoperiod-sensitive genetic male sterile (PGMS) line (Shi 1981). The development of environmentally induced genetic male sterile (EGMS) rice, including PGMS, thermosensitive genetic male sterile (TGMS), and photo-thermosensitive genetic male sterile (P-TGMS) lines laid the foundation for using a two-line system for the production of hybrid rice seeds. Up to 2010, the total planting area for two-line hybrids amounted to 24.5 million m^2 and 21% of the total planting area for hybrid rice. Based on the experience with high yield breeding for hybrid rice in China and the experience with the new plant type (super rice) breeding at IRRI, a special collaborative research project on breeding for super rice was established by the Ministry of Agriculture (MOA) in China in 1996 (MOA China 1996). This project defined super hybrid rice as the varietal type combining the ideotype plant with heterosis through hybridization between indica and japonica varieties to achieve super high yield (Cheng et al 1998).

Hybrid rice outyields the leading conventional varieties by 10–20%, thus enabling China to increase its rice production by nearly 550 million tons, with 480 million ha of hybrid rice from 1976 to 2011. So far, hybrid rice has been developed for 50 years. The area under hybrid rice increased from 0.14 million ha in 1976 to about 18 million ha in recent years, more than 60% of the total rice-planting area in China (Table 1). In some regions, such as Jiangxi and Sichuan provinces, more than 90% of their rice varieties belong to hybrid rice. Several thousand hybrid rice varieties have been released in the past 50 years. Research on hybrid rice can be divided into three generations according to the development performance of these hybrids. The first-generation representative hybrids were Nanyou2, Shanyou 2, and Vyou 6, among others, and these were characterized as IRRI's elite IR24 and IR26 and were used directly as restorer lines. The second-generation representative hybrids were Shanyou 63, Vyou 64, and Shanyougui33, among others, and these were characterized as new restorer lines derived from IRRI's elite lines. For instance, the most famous restorer line in China was Minghui63, developed from IR30. A total of 34 hybrids had been released by directly using Minghui63 as a restorer line and more than 900 hybrids have been released using other restorer lines derived from Minghui63. The third-generation representative

Table 1. Yearly area of hybrid rice and percentage of the total rice area in China in 1976-2010.

Year	Hybrid rice planting area (million ha)	% of total rice area
1976	0.14	0.4
1978	4.34	12.6
1982	5.62	17.0
1986	9.00	27.9
1990	13.62	41.2
1997	17.73	55.8
1999	16.55	52.9
2002	15.48	54.9
2005	19.01	65.5
2008	18.45	63.1
2010	18.05	60.2

hybrids were super hybrid rice, including three-line super hybrid Xieyou 9308 and two-line super hybrid Liangyoupei9. Super hybrids were characterized with strong intersubspecific heterosis in combination with the ideotype plant.

China has made a great effort to increase its rice yield through exploiting rice genetic resources. The performance of the rice sector in terms of production and yield had been quite impressive in most of the last five decades. With the wide adoption of semidwarf varieties with the *sd1* gene, rice yield per unit area in China increased from 2.0 t/ha in the 1960s to 3.5 t/ha in the 1970s. Subsequently, hybrid rice that has a yield advantage of 10–20% over conventional varieties was developed and commercially grown in 1976, which resulted in an increase in yield to more than 6.0 t/ha. Up to now, a total of 96 super rice varieties were confirmed by the MOA and were released to farmers since the MOA began the super rice breeding program in 1996. The planting area of super rice occupied 25% of the total rice planting area and reached 7.3 million ha in 17 provinces in 2011 (Fig. 1). These hybrid rice varieties have already made an important contribution to food security in China.

Experience with hybrid rice breeding

China is the first country successfully exploiting hybrid rice commercially on a large scale in the world. The experience is attributed to the use of various CMS resources, the high outcrossing rate of CMS lines and stable EGMS lines, improvement of resistance to diseases and grain quality, and the combination of an ideotype plant with heterosis in the hybrid rice breeding program. In the past 10 years, more and more two-line hybrid rice varieties have been released. However, three-line hybrid rice varieties still occupy the dominant place in rice production in China. The three-line system has been considered as the most effective system for developing rice hybrids in China. More than half of the total rice varieties released at the national and provincial level were three-line hybrid rice varieties in 2010 (Fig. 2).

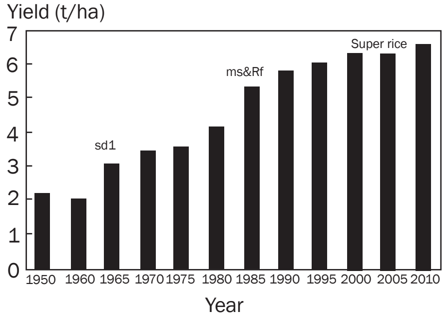

Fig. 1. Increase in rice yield through genetic improvement in China.

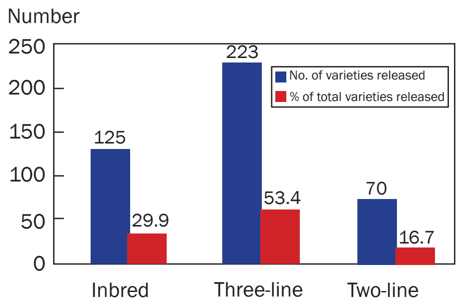

Fig. 2. Number of different rice varieties released at national and provincial level (2010).

Three-line hybrid rice breeding

Exploitation of various CMS resources. Wild-abortive (WA) type CMS was the first type to be used in hybrid rice breeding. So far, the combination of CMS-WA is still the dominant one in terms of three-line hybrid rice production. To minimize the potential damage from rice diseases caused by the unique CMS genetic background, Chinese rice scientists have exploited other CMS lines and developed different CMS lines for breeding new combinations of hybrids. There are, in total, eight kinds of CMS lines being used in China's hybrid rice breeding program (Table 2). Three main types of CMS resources are used in rice production: CMS-WA, CMS-ID, and CMS-G&D. In regard to planting area in recent years, the combinations of CMS-ID and those of CMS-G&D took second and third places for CMS hybrids, respectively (Fig. 3).

Development and use of elite CMS lines with high outcrossing rate. With the rapid application of hybrid rice, high yield is not the only breeding goal. Rice quality and low-cost hybrid rice seed are emphasized in rice production and trade. Therefore, CMS lines with good quality and a high outcrossing rate were cultivated by rice breeders. Along with the use of these excellent CMS lines, a series of high-yielding and good-quality hybrid rice combinations were released to farmers. In terms of quality

Table 2. Eight CMS resources used in three-line hybrid rice breeding.

CMS resource	Origin
WA	Wild-abortive rice in Hainan
G	Gambiaka from west Africa
D	Indica rice Dissi D52/37
ID	Indonesia 6 from Indonesia
DA	Dwarf wild rice in Jiangxi
K	Japonica rice K52
HL	Red-awned wild rice
BT	Chinsurah Boroll/Taichong65
DT	Japonica rice Taibei 8

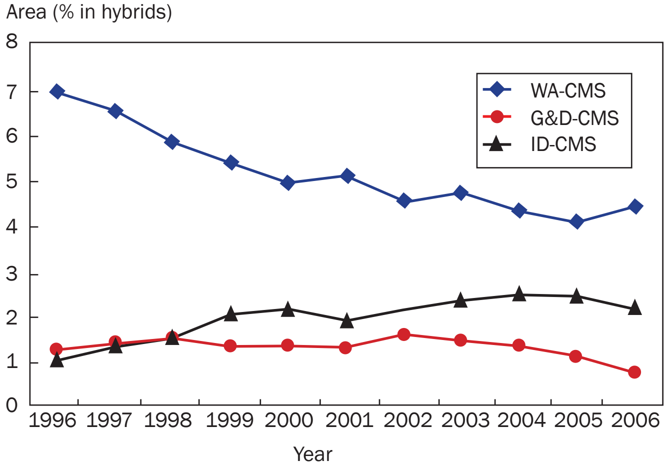

Fig. 3. The contribution of different CMS types to hybrid rice production in China.

and outcrossing rate, CMS lines of second-generation hybrid rice were significantly better than those of first-generation hybrid rice. Zhenshan97A, a famous WA-CMS line, was widely used for first-generation hybrid rice in the 1980s. It was developed by the Jiangxi Rice Research Institute. Zhong 9A and Chuanxiang29A were widely used in the 21st century and belonged to CMS lines of second-generation hybrid rice. Those two CMS lines were developed by the China National Rice Research Institute (CNRRI) and Sichuan Academy of Agricultural Science, respectively. Zhong 9A and Chuangxiang29A showed good quality and high outcrossing rate compared with Zhenshan97A (Table 3). Now, more good agricultural traits receive more attention such as disease resistance, good flowering habit, etc.

Marker-assisted selection (MAS) for restorer lines of hybrid rice. Most first-generation restorer lines were susceptible to diseases or had only single resistance to

Table 3. Performance for grain quality and outcrossing rate of Zhenshan97A, Zhong 9A, and Chuanxiang29A.

Performance	1st-generation CMS line	2nd-generation CMS line	
	Zhenshan97A	Zhong 9A	Chuangxiang29A
CMS resource	WA	ID	WA
Grain length/width ratio	2.3	3.1	2.4
Chalky grain percentage (%)	84.0	8.0	48.0
Chalkiness (%)	16.6	0.6	10.8
Translucencya	4	3	3
Exserted stigma (%)	39.6	82.3	66.8
Outcrossing seed setting (%)	35.7	75.6	69.5
Seed yield (t/ha)	2.2–3	3.0–4.5	3.0–4.5
No. of hybrids released		112	31

[a] On a scale of 1–4, where 4 = the lowest grade and 1 = the highest grade.

diseases. However, the second- or third-generation restorer lines had dual resistance such as resistance to blast and bacterial blight diseases. Rice blast and bacterial blight are two of the most destructive diseases that lead to severe yield losses in rice production in China. The most effective approach to prevent the two diseases is genetic improvement using resistant varieties. With few exceptions, control of rice diseases depends on main-effect resistance genes in host varieties. With the rapid development of molecular biology techniques, molecular marker-assisted selection began to be widely used in breeding research in the past 10 years. This technology can aid in the identification of offspring with two or more genes by molecular markers closely linked with the target gene.

Now, a series of restorer parents developed by CNRRI such as Zhonghui 8006 (*Xa4* + *xa5* + *xa13* + *Xa21*), Zhonghui111 (*xa5* + *Xa21* + *Pi25*), Zhonghui 161 (*Pib* + *Pita* + *Xa4* + *xa13*), Zhonghui8012 (*Xa21* + *Xa23* + *Pi25*(t)), and Zhonghui 8015 (*Pi25* + *Xa21*) show good disease resistance and are used as key parents for hybrid rice (Fig. 4). These restorer lines with multiple resistance showed that MAS is a feasible tool for effectively pyramiding multiple resistance genes (Cao et al 2003, Cheng et al 2004). Moreover, this technology can also pyramid other genes important for agronomic traits into restorer lines. CNRRI has constructed a DNA marker database for key parents of hybrid rice, including traits of resistance, grain quality, and yield. All the data can be found at www.ricedata.cn/gene.htm.

Two-line hybrid rice breeding

The planting area of two-line hybrid rice has been growing rapidly in the past 15 years. Two-line hybrid rice covers almost all of southern China. The planting area of two-line hybrids has surpassed that of three-line hybrids in Anhui, Hubei, and Hunan provinces. Recent research on two-line hybrid rice has made important progress in two areas.

One is to strengthen the selection pressure for the development of TGMS lines with low critical temperature of fertility transformation through artificial cool-water

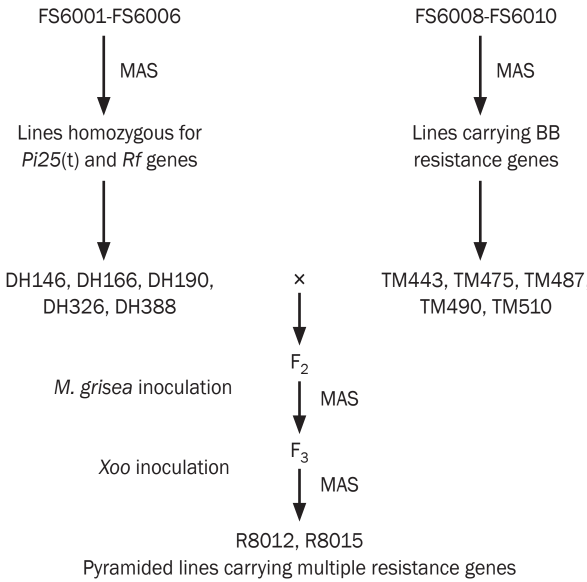

Fig. 4. Breeding flowchart of R8012 and R8015 with MAS technology.

irrigation. Critical temperature is the most important parameter for TGMS lines. When the temperature in the key growth duration period is above the critical temperature, TGMS lines will be sterile; otherwise, TGMS lines will become fertile. When the natural temperature is lower than the critical temperature, the self seed setting of TGMS lines will result in failure of hybrid seed production. On the contrary, when the natural temperature is higher than the critical temperature, low seed setting of TGMS lines will result in failure of TGMS line seed production. Dongtai, located in Jiangsu Province, is a good place to have two-line hybrid seed production in China. However, Dongtai's weather data analysis indicated that it is unsafe to produce hybrid seeds in the summer if the critical temperature of TGMS lines surpasses 24 °C. Therefore, the artificial cool-water irrigation system can provide breeders with an effective platform to screen good TGMS lines with low and stable critical temperature of fertility transformation. In the past several years, many artificial cool-water irrigation systems for two-line hybrid rice breeding were built. A series of TGMS lines with low critical temperature was cultivated. For instance, the critical temperature of TGMS line C815S is 22 °C, which is suitable for the safe production of hybrid seed. This TGMS line is widely used in the Yangtze River region.

The other research area is to increase the yield of hybrid seeds by selecting a suitable location with stable natural temperature. Hunan Agriculture University successfully built the system of computer decision for TGMS seed production (SCD-TGMS-SP) in 2010. This system consists of different models and human-machine conversation interface (Fig. 5). Regarding different TGMS lines, this system can suggest an ideal location for TGMS seed production and suitable sowing time. For example, according to the information on TGMS C815S, this system simulation shows

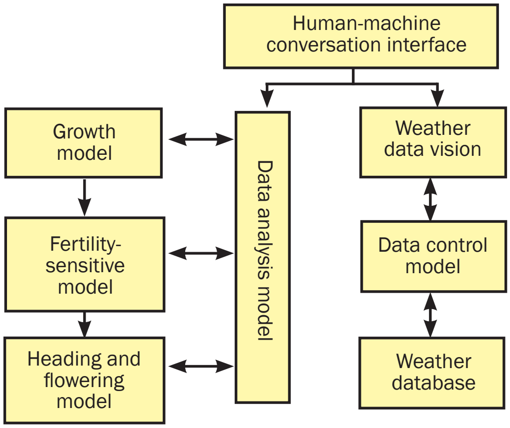

Fig. 5. A computer decision system for TGMS seed production.

that Baoshan, Yunnan Province, is the best region for seed production and the fertility transfer start date is 5 August. With the aid of SCD-TGMS-SP, the yield of C815S seed production reached 8.44 t/ha in Baoshan, Yunnan, in 2010.

Future research and development of China's hybrid rice

Hybrid rice has contributed greatly to self-sufficiency of the food supply in China. To meet future demand for rice production, raising the yield ceiling of rice remains a priority. However, further increases in rice yield seem to be more difficult. Several issues for future research on and development of China's hybrid rice should be considered.

Enhancing the genetic diversity of parents

To further increase the yield potential of hybrid rice, first we should enhance the genetic diversity of parents. The breeding strategy is to use hybrid heterosis between indica and japonica. For the past decade, more and more medium-type restorers or CMS lines in subspecies differentiation have been applied in hybrid rice breeding programs in China. In the indica rice-growing regions of China, breeders adopted the methodology of introgressing japonica blood into an indica rice background to develop indica-inclined germplasm, and in the japonica rice-growing regions introgressing indica blood into a japonica rice background to develop japonica-inclined germplasm. So far, a series of indica-inclined or japonica-inclined germplasm for super rice breeding has been deliberately developed (Fan et al 1999, Cheng et al 2004). Some of the germplasm has been successfully used in breeding super hybrid rice. For instance, the first generation of super hybrid rice Xieyou9308 was hybridized between CMS XieqingzaoA and restorer R9308. XieqingzaoA, an indica-type CMS line, has 3.5% japonica genetic components. R9308 is a medium-type restorer and it has 21% japonica genetic components. Xieyou9308, released in 1999, showed strong heterosis and yielded 12.2 t/ha at a demonstration trial in Zhejiang Province in 2000. Another example is the second generation of super hybrid rice Yongyou12. This hybrid is an indica-japonica super hybrid with a 49% japonica genetic base. It was crossed between CMS Yongjing2A and restorer F5032, which have 89.5% and 7.9% japonica genetic components, respectively. The yield per unit of Yongyou12 in a demonstration trial reached 14.2 t/ha in Zhejiang Province in 2011.

Selecting an ideotype plant to increase photosynthesis efficiency

Another approach is selecting an ideotype plant to increase photosynthesis efficiency synchronously considering both aboveground and underground traits, especially the root system. The ideotype plant is to ensure super hybrid rice with high root vigor and more functional leaves in the late growth stage (Cheng et al 2005, Wu et al 2005). Root vigor at the late developmental stage directly affects the life span of functional leaves and grain filling. It is a guarantee for high yield of super rice (Zhai et al 2002, Wu et al 2006, Cao et al 2010). Root system vigor at various growth stages, particularly during the grain-filling period, should be comprehensively considered in super hybrid rice breeding. CNRRI used the water-face planting method to study the root system. This method can simply and quickly sample without damaging the root system. The parameters relative to high root vigor of rice in the late growth stage were defined on the basis of massive screening trials. Main root length (MRL) is the most important root parameter in a super rice hybrid breeding program. QTL qMRL7 linked to MRL was mapped on the short arm of chromosome 7. Regarding super hybrid rice, the root depth index was more than 10 at heading stage and was more than 40 days at the functional photosynthesis stage. Without a doubt, these studies are still preliminary. Further systematic research relative to gene regulation of the root system and the relationship between aboveground and underground parts of the plant should be given more attention. Meanwhile, for rice breeders, simple methods for appraisal or effective indicators to screen high root vigor will be more helpful.

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Notes

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Hybrid rice in India: prospects and future challenges

E.A. Siddiq and A.S. Hari Prasad

Since the revival of interest in hybrid rice technology in the mid-1990s for sustaining the growth trends of rice production and productivity, which had started declining, India did make progress and earned the distinction of being the second-largest hybrid rice-growing country after China. Progress in terms of pace of adoption, however, continues to be far short of what was targeted largely on account of it not being attractive enough and having inconsistent yield performance/advantage, less acceptable cooking quality, limited choice of crop growth duration, vulnerability to biotic stresses, shortage of quality seed, and nonaffordable seed cost. Wide acceptability and extensive adoption of the technology would depend, therefore, on correction of the deficiencies and constraints, and this warrants aggressive augmented research intervention, large investment in research and development, and a favorable policy environment. As for research, breeder involvement in hybrid rice breeding is less than one-tenth of the number in China, and the level and continuity of funding for hybrid rice research and development are disappointing. The technology has yet to make its spread and impact in regions/states where it is more relevant. The policy environment is not yet favorable and inclusive enough for the private sector to actively partner with public institutions in technology development and seed production. There is also room to rationalize and speed up the process of testing and release of hybrids. If these problems are addressed with priority, given the research initiatives underway and the progressively improved hybrid versions, the prospects of the technology covering about 50%, 30%, and 100% of the irrigated, favorable rainfed shallow lowland, and boro ecosystems, respectively, and thereby meeting future demand projections of the nation, are high.

The development and demonstration of the commercial feasibility of hybrid technology in China by the late 1970s marked the second major landmark in the history of rice breeding. Impressed with how the technology found extensive adoption and enabled China to achieve major breakthroughs in rice production and productivity, many countries in tropical Asia revived interest in hybrid rice breeding. India, keen to replicate China's success story with hybrid rice, accelerated research through a network approach at the national level in 1990. The effort, with funding support from UNDP/FAO, ICAR, and Mahyco (Barwale) Foundation and technical input from IRRI and China, helped the country to come up with first-generation hybrids for commercial planting by 1995. Unlike China, where the pace of adoption of the technology was rapid and covered about 18 million hectares in 15 years since its introduction, India could not as yet surpass 2 million ha, despite higher yielding hybrids available for the major rice-growing states and a strong seed production-marketing system in place. This study briefly discusses the state of hybrid rice, the factors that slow down the pace of adoption, ongoing research to correct the deficiencies of the earlier released hybrids, and development and policy interventions needed to accelerate adoption to cover 10 million ha by 2020.

Hybrid rice in India: status

Revived as late as 1990, exclusively as a modest public-sector initiative, hybrid rice research in the country grew over the next 10 years as a large vibrant public-private sector program. Together, public institutions and the steadily increasing number of seed companies in the private sector have been successful in evolving and commercializing as many as 90 hybrids to date. Of the 59 notified hybrids, 45 are from the private sector (Table 1).

Significantly, the private sector accounts for more than 80% of the hybrid seed produced and marketed. If the present trend is any indication, it is more likely that the entire hybrid seed need of the country will be met by the private sector in the coming years.

Area planted to hybrids reveals low productivity in Uttar Pradesh, Bihar, Chhattisgarh, and Jharkhand, accounting for more than 75% of the hybrid rice area (Table 2).

This trend, though a welcome development, is disappointing as the originally targeted high productivity states such as Punjab, Tamil Nadu, Andhra Pradesh, and

Table 1. Source of notified hybrids.

Source/duration	Number of hybrids	Popular hybrids
Public		
Early	11	DRRH 2, Sahyadri 4
Mid-early	10	Pusa RH 10, Ajay
Medium	10	KRH 2, DRRH 3, CRHR 32
Private		
Early	3	PA 6129
Mid-early	12	PA 6201, US 312, DRH 775, GK 5003
Medium	12	PHB 71, JKRH 401, HRI 157
Medium-late	1	PA 6444
Total (E14, ME22, M22)	**59**	

Table 2. Major hybrid rice-growing states in kharif 2011 (based on F_1 seed sold).

State	Area (000 ha)
Uttar Pradesh	782
Bihar	328
Jharkhand	212
Chhattisgarh	207
Haryana	99
Madhya Pradesh	83
Gujarat	80
Odisha	53

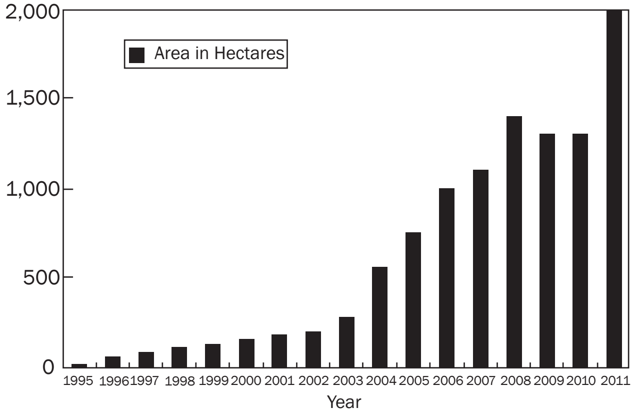

Fig. 1. Pace of the adoption of hybrid rice in India (1995-2011).

the northwestern segment of the Indo-Gangetic Plains hardly have any area under hybrid rice. The only state in northwestern India with a reasonable area under hybrids is Haryana and this exception is due to the release in 2001 of Pusa RH10, the first-ever hybrid of basmati quality. Adoption of the technology remained very slow until 2000, with steady and significant growth since 2006 (Fig. 1).

The increase in the adoption rate during the last five years is obviously due to growing interest and preference among farmers to grow hybrids instead of relatively low-yielding varieties in low-productivity states/regions such as eastern Uttar Pradesh, Bihar, Chhattisgarh, and Jharkhand.

Factors impeding the pace of adoption of hybrid technology

Although hybrid rice is a proven and the only readily available technology capable of raising substantially the ceiling on the genetic yield of rice, the pace of its adoption is disappointing and far short of our expectations. Experience with the trend of acceptability of the technology at the farmer, trader, and consumers levels suggests the following as the major reasons for its slow adoption.

Less attractive yield advantage

In farmers' perspectives, the yield advantage of hybrids over the best high-yielding varieties is not attractive enough, unlike their experience with maize, sorghum, and pearl millet hybrids. In high-productivity states such as Punjab, Haryana, Tamil Nadu, and Andhra Pradesh, the yield of high-yielding semidwarf rice varieties is around 8 t/ha as against about 9 t/ha possible from hybrids. The 1 t/ha advantage is hardly economically advantageous in the face of rapidly rising production costs. In low-productivity rainfed eastern India, a yield advantage of hybrids in the range of 1.0 to 1.5 t/ha is attractive, and hence, farmers in the predominantly rainfed states of eastern Uttar Pradesh, Bihar, Chhattisgarh, Jharkhand, etc., increasingly opt for hybrids.

Inconsistent yield performance/advantage

Aside from low yield and limited yield advantage, inconsistent yield performance/advantage over years and locations is a matter of concern to farmers. Currently available hybrids across maturity groups do not perform consistently and hence have an inconsistent yield advantage. Analysis of the yield performance of the early, mid-early, and medium-maturing hybrids PA 6129 and KRH 2, respectively, over five locations and three consecutive years, for instance, shows the yield and yield advantage over the inbred checks to be highly inconsistent (Table 3a, b, c).

Lack of medium and medium-late hybrids

More than 85% of rice is grown in the wet (kharif) season, for which medium (135 d) and medium-late (140–145 d) maturing hybrids are ideal. A majority of the currently available hybrids are of early and medium-early maturity. Unlike in many of the tropical Asian countries, including China, the Philippines, Indonesia, etc., the hybrid breeding objective has been for early and medium-early hybrids. With India and Bangladesh having sizable area under rainfed and mainly irrigated lowland systems, medium/medium-late hybrids are ideal and preferred. Except for a few later developed hybrids, most of the notified and truthfully labeled hybrids are early/medium-early hybrids, thus restricting the choice of hybrids for the long monsoon season (Table 4).

Less acceptable cooking and milling quality

The cooking quality of rice is determined by the physico-chemical properties of starch. Rice consumers in India in general and particularly those in the traditional rice-growing southern and eastern provinces prefer and are used to dry flaky cooking rice, which is of high amylose content (>25%). Basmati rice of northwest India characterized by less than intermediate amylose (20–22%) is the only exception to the starch properties of the typical indica rice. All the hybrids, except for a few of the latest additions, are not only of low amylose (<20%) content and hence sticky upon cooking but also aromatic. This is because of the use of the very low amylose and aromatic IR58025A as the male sterile line (seed parent) in the development of nearly all the commer-

Table 3a. Inconsistent yield performance of popular early hybrid PA 6129 over locations and years.

Location	Year (yield in kg/ha)		
	2009	2010	2011
Coimbatore	8,033	7,016	10,974
Ludhiana	7,667	3,160	4,134
Chiplima	4,527	5,467	3,503
Nawagam	8,902	1,407	5,581
Mandya	11,827	7,964	9,423
Mean	6,826	5,003	6,723
Inbred check mean	5,885	4,675	5,674
Yield advantage over the inbred check (%)	16	7	19

Table 3b. Inconsistent yield performance of popular medium-early hybrid PA 6201 over locations and years.

Location	Year (yield in kg/ha)		
	2009	2010	2011
Coimbatore	7,573	7,311	11,770
Ludhiana	–	5,565	4,368
Chiplima	5,007	5,556	4,410
Nawagam	7,765	4,221	4,592
Mandya	8,874	6,315	8,799
Mean	7,305	5,794	6,788
Inbred check mean	6,904	5,176	6,026
Yield advantage over the inbred check (%)	6	12	13

Table 3c. Inconsistent yield performance of popular medium-duration hybrid KRH-2 over locations and years.

Location	Year (yield in kg/ha)		
	2009	2010	2011
Coimbatore	7,533	5,098	9,865
Ludhiana	6,306	6,863	6,145
Chiplima	6,330	6,173	4,801
Nawagam	8,838	2,814	6,151
Mandya	8,386	6,625	7,466
Mean	7,479	5,515	6,886
Inbred check mean	6,418	5,478	6,513
Yield advantage over the inbred check (%)	17	1	6

Table 4. Duration range of commercially planted hybrids.

Duration (seed to seed in days)	Number of hybrids	Promising hybrids
Early (<120 d)	14	DRRH 2, Sahayadri 4, PA 6129
Mid-early (121–130 d)	22	Pusa RH10, Ajay, Indam 200 017, PA 6201, DRH 775, VNR 204
Medium (131–145 d)	22	JKRH 401, PA 6444, KRH 2, PHB 71, CRHR 32, JKRH 3333, HRI 157, Rajalaxmi, Sahyadri 5
Medium-late/late (>145 d)	1	NPH-924-1

cially planted hybrids. Especially hybrids that involved IR58025A and high-amylose R lines (pollinator parent) have sticky and nonuniformly cooked grains, the harvest from hybrids (F_1) being F_2 grains that segregate for amylose content, gelatinization temperature, and gel consistency. This has been the major reservation against hybrids among consumers as well as traders in the traditional rice-consuming areas (Table 5).

Millers have had reservations against hybrids on account of the low percentage of head rice milling recovery (high percentage of kernel breakage on milling). Although no scientific reason is as yet known for this undesirable milling quality of hybrids, the very perception wrongly or rightly of this effect has been causing hybrids to receive a lower price in the market than the price offered for varieties. The price difference is said to nullify the expected gain from yield advantage, which in a way justifies the reservation of farmers against hybrids. Some recently released hybrids are reported to be of acceptable cooking (high amylose) and milling (high head rice milling recovery) quality (Table 6).

Vulnerability to major insect pests and diseases

All the early-generation hybrids are susceptible to most of the major pests such as blast, bacterial blight, sheath blight, false smut, hoppers, gall midge, etc., and yield losses as a result used to be substantial, depending on the amount of pest incidence. This was not an unexpected deficiency as breeding for tolerance of biotic stresses did not receive as much emphasis as yield vigor and yield advantage. Over the years, the spectrum of resistance to pests has broadened considerably. Unlike early-generation hybrids, many of the recently released ones combine resistance to more than two major pests (Table 7).

Research toward correcting trait deficiencies

Recognizing that correcting trait deficiencies through selective improvement of parental lines is the way to sustain and gain from hybrid technology, there has been a conscious breeding effort to evolve parental lines of medium/medium-late maturity, intermediate/high amylose content, devoid of basmati aroma, and with broad-spectrum resistance to major pests.

Public-bred male sterile lines of medium/medium-late maturity such as CRHR 32A combining high/intermediate amylose content and no aroma along with those

Table 5. Hybrids of acceptable cooking and milling quality.

Grain quality[a]	Hybrids
Good milling and starch quality	Rajalaxmi, CORH 3, PA 6129, GK 5003, HRI 157, HRI 169, JKRH 401, 27P25, 27P31, PNPH 24, US 382, RH 1531, VNR 202, VNR 204, NPH 924-1
Good cooking and nonaromatic	NK 5251, PA 6201
Good cooking and aromatic	US 312, KRH 2, Pusa RH 10, DRH 775
Ideal cooking and grain quality	DRRH 3, TNAU Rice Hybrid Co 4, 27P61, 27P11, JKRH 3333

[a]Good cooking quality: intermediate to high amylose content.
Good milling quality: head rice mill recovery >60%.
Ideal cooking and grain quality: similar to samba Mahsuri (BPT 5204).

Table 6. Starch characterized and cooking quality of commercially planted hybrids.

Amylose content	Number of hybrids[a]	Hybrids
Low (<20%)	3	HKRH1, Pant Shankar Dhan 3
Intermediate (21–25%)	37	PHB71, PA 6444, PA 6201, Pusa RH10
High (>25%)	14	Ajay, Rajlaxmi, APRH2, DRRH 2

[a]Estimation based on flour sample of grains harvested from F_1 (hybrid) plants (Source: DRR).

Table 7. Hybrids resistant to major pathogens and insect pests.a

Resistant to	Number of hybrids	Important hybrids
6 pests	1	US 382
5 pests	4	Ajay, CORH 3, Sahyadri 4, HRI 169
4 pests	8	PA 6444, Pusa RH 10, Rajalaxmi, JKRH 401, PA 6201
3 pests	12	DRRH 3, US 312, VNR 202, 27 P 31
2 pests	8	PAC 835, DRH 775, Indam 200-017
1 pest	5	PA6129, CRHR 32, Sahyadri 5

[a]Scored for blast, bacterial blight, RTV, SB, BPH, and WBPA.

developed by the private sector are now enabling the development of hybrids suitable for a long wet season in the traditional as well as nontraditional rice-growing regions. Recently identified hybrids such as Rajalaxmi and CRHR 32 are found to meet reasonably well the trait requirements for the long kharif/samba seasons of coastal Andhra Pradesh and the delta of Tamil Nadu as well as rainfed and mainly irrigated shallow lowland ecosystems in eastern states such as Odisha and West Bengal.

Medium-late maturing Rajalaxmi and CRHR 32 are the first-ever hybrids developed for rainfed shallow lowland ecosystems. Breeding research underway at the Central Rice Research Institute, Cuttack, for insulating such long-duration hybrids with tolerance of drought and submergence would help to achieve more ideal hybrids for such handicapped ecosystems. Incidentally, hybrids of medium to medium-late maturity yield relatively higher with an enhanced yield advantage compared with those of early and medium-early duration.

Simultaneously, breeding to insulate hybrids with broad-spectrum resistance against major pests and their virulent variants employing a molecular marker-assisted strategy has led to the development of parental lines pyramided with pest and race-biotype-specific resistance. Many hybrids evolved using such improved parental lines are now in the advanced stages of evaluation under the All India Coordinated Testing Program.

As for enhancing genetic yield, breeding efforts are underway to exploit more heterotic intersubspecific (indica/tropical japonica) hybrids by overcoming the problem of persistent hybrid semisterility, characteristic of indica/japonica hybrids, by introgressing spikelet sterility-neutralizing (wide compatibility) gene loci. Indica as well as japonica parental lines such as RPHR 612, RPHR 619, and RPHR 1096 carrying appropriate wide compatibility gene loci are now available for developing fully fertile intersubspecific hybrids and those lines showing high combining ability are being used to evolve highly heterotic intersubspecific hybrids. Some of the test hybrids of indica-japonica origin now in advanced station trials and All India Coordinated Trials appear promising from yield/yield advantage angles. Simultaneously, research is pursued to develop intersubspecific hybrids in a new plant type background for realizing still higher yield vigor.

Favorable factors for and constraints to the extensive adoption of hybrid rice

Bringing 5 and 10 million ha under hybrid rice by 2015 and 2020, respectively, should not be an unachievable task, given the (1) pace at which new-generation hybrids devoid of many of the trait deficiencies and ideally suited to irrigated and relatively favorable rainfed lowland ecosystems are being produced, (2) increasing interest and active involvement of the private sector in hybrid rice research, (3) launch of the New Hybrid Rice Research Network by ICAR during the current planning period for strengthening hybrid rice research, (4) large and vibrant seed industry with proven capability in quality hybrid seed production and supply, (5) public policies favorable to the development and extensive adoption of hybrid rice technology, and (6) a farming community increasingly receptive to adopting hybrid rice technology.

While exploiting the factors favorable to the wide adoption of hybrid rice technology, it is equally important to address the problems that constrain the pace of adoption. These include (1) the lack of ideal and stably performing hybrids for productive ecosystems such as rainfed shallow lowlands and the boro season; (2) the lack of a strong institutional mechanism for the production and supply of quality seed of public-bred hybrids; (3) no uniform subsidy on hybrid seed cost, which varies from state to state; (4) the price discrimination against hybrids (paddy) because of low percentage head rice milling recovery; (5) the very low number of breeders (<20) involved in hybrid breeding in the public sector in the country as against many more (>150) in China; and (6) the weakening extension strategy for the popularization of region-ecology-specific hybrids.

An action plan for achieving the short-term target

The following action plan is suggested for 5 million ha under hybrids by 2015:

- Identification of 20 stably productive region- and ecology-specific hybrids for an extensive compact block frontline demonstration. The suggested hybrids for potential regions and ecosystems follow:

Ecosystem	Region/state	Choice of hybrids[a]	
Irrigated	Eastern UP, Bihar Jharkhand, Chattisgarh, Assam, Tamil Nadu, Andhra Pradesh	Early	PA 6129
		Mid-early	GK 5003, PAC 837, US 312, PA 6201, DRH 775, Indam 200-017
		Medium	PHB 71, PA 6444, DRRH 3
Rainfed shallow lowland	Eastern India	Rajalaxmi, CRHR 32	
Boro	Eastern India	Rajalaxmi, CRHR 32, NRH 924-1	
Basmati	Northwestern India	Pusa RH10	

[a]The list of hybrids to be critically assessed and added/deleted.

- Strengthening of the existing institutional mechanism for the production and supply of breeder, foundation, and certified seed. The National Seed Corporation, State Farm Seed Corporation, and State Seed Corporations need to be strengthened with competent plant breeders.
- Large-scale training of farmers in integrated crop management (IMC) for hybrid rice cultivation.
- Development of a sustainable mechanism for the production and marketing of seed of public-bred hybrids by the private seed industry on mutually agreed terms.
- A uniform and reasonable (75%) subsidy on seed cost for new-generation hybrids for 5 years.

Conclusions

Though hybrid rice is a proven technology with a higher yield threshold, no country has yet fully exploited its potential except for China. As for India, despite scope to meet future rice demand by narrowing the wide yield gap that still exists in high-yielding semidwarf varieties, to remain self-sufficient 10 years from now will not be easy in the absence of technologies capable of further raising genetic yield by 15–20%. The country introduced hybrid rice technology more than 15 years ago with a 10–15% yield advantage. Sadly, India is still far from what China has achieved and benefited from, largely on account of a lack of research-extension thrust to the desired extent and a supportive policy environment. It would be wise for the country to prioritize this readily available technology by progressively improving its productivity and stability and thereby gaining increasingly from both favorable irrigated and relatively favorable rainfed lowland ecosystems.

Notes

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Hybrid rice breeding perspective from the private sector

Yog Raj

The world population has surpassed 7 billion and as per estimates from the United Nations it will reach 9 billion by 2050. About 97% of the growth in population is estimated to come from the developing world, specifically Asia and Africa. Asia accounts for about 90% of global rice production and consumption as well. In proportion to this population growth, out of a total of about 116 million tons of additional rice needed by 2035, about 100 million tons are required in Asia and Africa.

As per the International Rice Research Institute, Philippines, hybrid rice is a key technology that can meet the increasing global demand for rice. China has shown the way by making initial developments and large-scale commercialization of hybrid rice technology. China now produces more than 65% of its rice from about 50% of the area under hybrid rice. Hybrid rice is being cultivated on about 21 million hectares in Asia, out of which more than 80% is grown in China (Fig. 1).

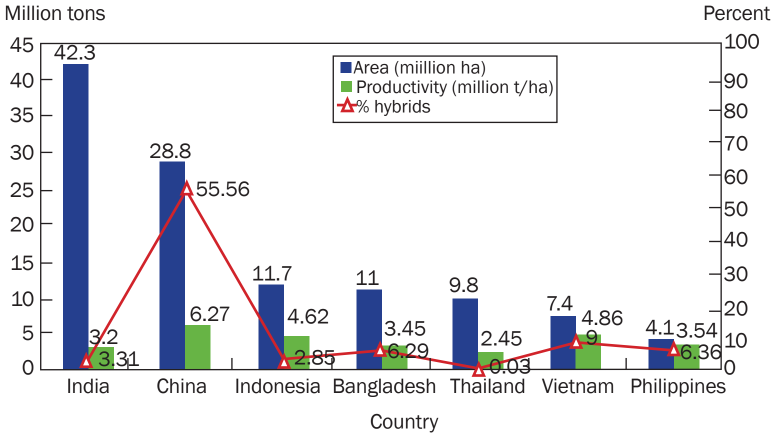

Fig. 1. The major rice-growing countries with total rice area, productivity, and area under hybrid rice.

The major driver for this large-scale adoption of rice hybrids is their higher yield advantage over inbred varieties and comparative hardiness in slightly stressed conditions. The large-scale adoption of rice hybrids has environmental benefits because of the following:

- With increased productivity, hybrid rice allows a reduction in total rice-growing area, thus making rice land available for agricultural diversification.
- Reduced usage of nitrogen fertilizers in highly fertile soils.
- Reduced water requirement due to shortened durations and efficient water absorption capacity with a stronger root system.
- Optimized crop protection with the introduction of biotic stress tolerance/ resistance.

In addition, hybrid rice is adding value for various stakeholders in society (Fig. 2).

Outside China, the commercial cultivation of hybrid rice in Asia has been accelerating at a faster pace for the past few years. The major countries keeping this pace are India, Vietnam, the Philippines, Bangladesh, Pakistan, and Indonesia, where, as per estimates for 2011, hybrids are being grown on about 4 million hectares. If efforts in R&D and extension of hybrid rice are further enhanced, the area under hybrids is expected to increase from about 11% currently to 30% of the target hybrid area by 2020.

Hybrid rice breeding and development efforts have helped India in successful large-scale commercialization. The major developments follow:

- A systematic network of ICAR institutions and state agricultural universities participated in goal-oriented hybrid development starting in 1989.

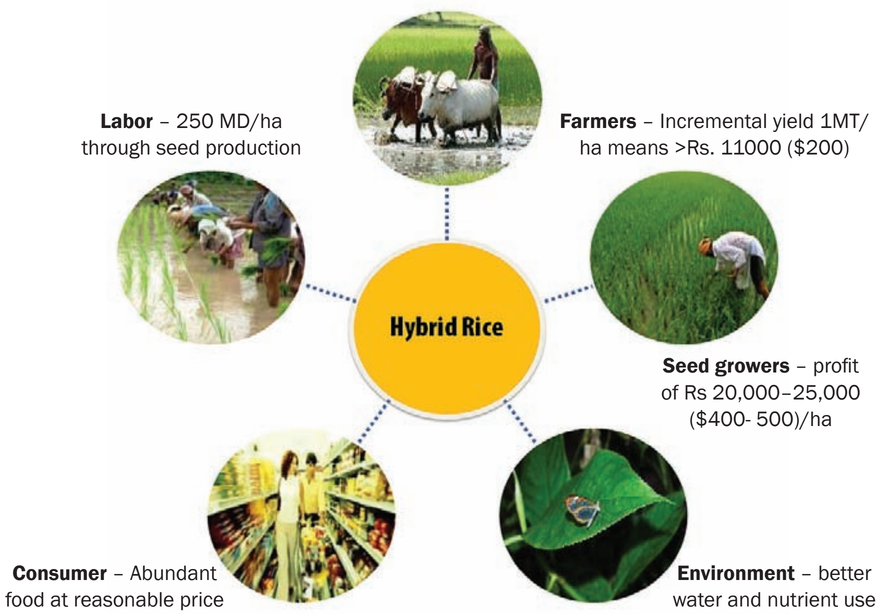

Fig. 2. A model showing the benefits of hybrid rice for various stakeholders in India.

- This helped in basic germplasm development, people development, and technology advancement for hybrid rice.
- During that same time, the private sector started its breeding and seed production research, and benefited from resources developed in the public sector.
- Initial hybrid performance and/or seed production posed limitations in early large-scale commercialization.
- Second-generation hybrids with better production during the early 21st century found favor with growers and farmers.
- Larger investment started in R&D in the private sector.
- About 45 hybrids were released in the country.
- Rice hybrids now cover nearly 2 million ha in farmers' fields.

In India, the commercialization of hybrid rice has grown with a comparative annual growth of about 20% for the past 8 years (Fig. 3). The major contribution in this commercialization is from private-sector seed companies. More than 90% of hybrid rice seed is now being supplied by private companies.

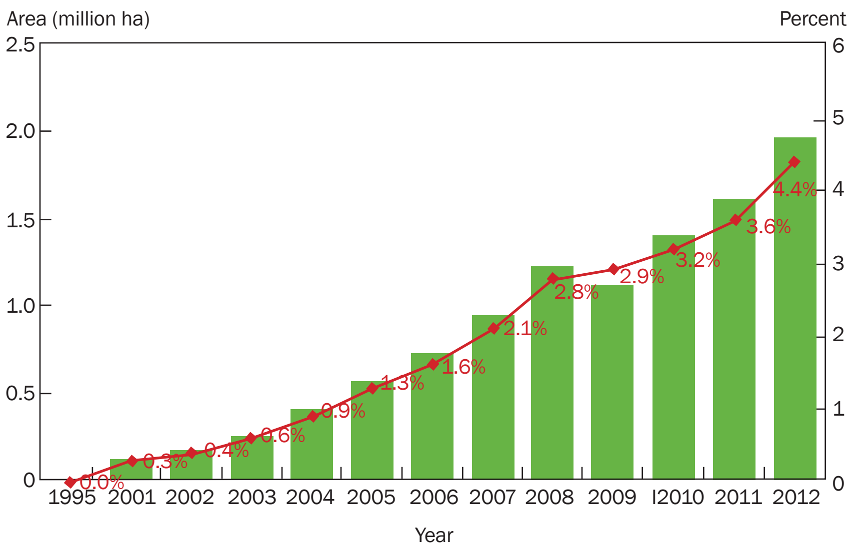

Fig. 3. Hybrid rice commercialization growth in India.

For faster dissemination of this technology, in addition to higher yield, companies are breeding and developing hybrids with good grain quality, tolerance of key environmental stresses, multiple resistance to insect pests and diseases, and high seed production yield. The future priorities for hybrid rice development follow:

- Encourage investment by the seed industry in hybrid rice R&D.
- Establish effective protection for innovation in breeding and crop biotechnology.
- Carry out genetic enhancement and develop heterotic pools.

- Develop specialized screening technologies.
- Develop molecular markers.
- Develop human resources through capacity-building initiatives.
- Allow free movement of germplasm and seed in line with international standards.
- Bring consistency to export/import requirements between different countries.

Hybrid rice adoption has allowed the world's most populous country to attain rice yields above 6 t/ha, one of the highest averages in Asia. Others can do the same.

Notes

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Progress in hybrid rice research and development at IRRI

Fangming Xie and Fulin Qiu

The International Rice Research Institute (IRRI) organized the Hybrid Rice Development Consortium to strengthen public and private partnership on hybrid rice R&D. The HRDC provides strong support to scientific research, product development, and capacity building. The priorities of hybrid rice R&D at IRRI are products with high yield and yield heterosis, improved outcrossing of female parents for high yield of seed production, and resistance to/ tolerance of biotic and abiotic stresses. Molecular marker technology is routinely used in product development.

Keywords: hybrid rice, heterosis, heterotic group, molecular markers, seed production

About 20.4 million hectares of rice land, which is about 12.4% of the total rice grown globally, grow hybrid rice in 2011. Hybrid rice technology has been applied in rice production across countries/regions of South and Southeast Asia, and the Americas, but mainly in Bangladesh, Brazil, China, India, Indonesia, Myanmar, the Philippines, Vietnam, the United States, and Uruguay (Table 1). The annual growing area for hybrid rice outside China increased from about 0.68 million hectares to 4.71 million hectares since 2001(Fig. 1), and the fastest-growing countries/regions in the last 5 years are India, Indonesia, and South and North America, where the area doubled to a total of 3.61 million hectares in 2011, which was about 67% of the total hybrid rice-growing area outside China. The major force for accelerating hybrid rice expansion in recent years is the large multinational and smaller national seed companies engaged in hybrid rice agribusiness. Investment for hybrid rice, not only for seed production but also for product R&D and capacity building, from private organizations has been increasing significantly in the last decade, which is making a significant impact on raising hybrid rice yield and expanding area. Public research institutes involved in hybrid rice R&D are gradually adapting a different system of new public and private partnership and collaborating with private organizations to disseminate hybrid rice.

After 35 years of hybrid rice R&D in the tropics, the International Rice Research Institute (IRRI), in collaboration with public research organizations and the seed industry, has made significant progress in hybrid rice product R&D, technology dis-

Table 1.Major hybrid rice-growing countries/regions with estimated growing area in 2010 (000 ha) outside of China.

	Country/region							
	Bangladesh	India	Indonesia	Myanmar	Philippines	Vietnam	Americas	Total
Area	700	2,000	650	78	180	595	509	4,712

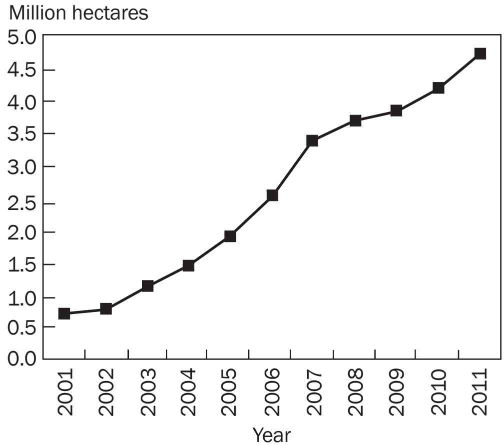

Fig. 1. Area grown for hybrid rice from 2001 to 2011 in countries outside China.

semination, and capacity building. However, as with other public partners, IRRI faces a challenge of establishing a new partnership with the public and private sector for hybrid rice development. To strengthen collaboration between the public and private sector for promoting hybrid rice development, IRRI organized an international Hybrid Rice Development Consortium (HRDC) with 38 public and private organizations as a new model for public-private partnerships in 2008. To foster this new public-private collaboration, IRRI concentrates more on prebreeding, basic research on key traits, information, and capacity building, whereas small and large private enterprises mainly promote commercialization and production, and need to have equal access to new traits, hybrid parental lines, pilot hybrid varieties, information, and other technologies developed by IRRI and the public sector. By the end of 2012, HRDC membership had increased to 61 members with 29 private organizations and 32 public research institutes from all over the world, but mainly from Asia. The HRDC provides not only demand-driven feedback for IRRI's hybrid rice research but also the financial support needed for sustaining it. Private organizations receive research products of this collaboration through fee-based, nonexclusive licensing mechanisms, whereas the public sector continues to have free access. This has allowed IRRI to double its hybrid rice breeding capacity and provide more breeding lines and other products for the hybrid rice community. HRDC members can also participate as sponsors of specific projects and seek bilateral collaboration with IRRI through Scientific Know-how and

Exchange Programs (SKEPs), focusing on joint research and capacity building, which not only benefit SKEP partners but also the general public involved in rice research because all experimental results and scientific reports are published internationally.

During the past 5 years, the HRDC at IRRI has been focusing its major efforts on the following research priorities based on feedback from its members:

- Develop heterotic rice hybrids and enhance yield heterosis;
- Increase and stabilize the yield of seed production;
- Improve resistance to diseases and insects, and hybrid rice grain quality;
- Develop hybrids for unfavorable environments; and
- Improve breeding efficiency by using biotechnology.

Developing heterotic rice hybrids and enhancing yield heterosis

With strong support from the HRDC, IRRI is still leading in product development of heterotic hybrids in the tropics. New hybrids and parents have been continuously released for commercial rice production. Since the first hybrid released for production in 1994, a total of 44 hybrids have been approved for rice production in the Philippines. Eleven of those 44 hybrids were developed at IRRI, and 6 of them were developed in the last 5 years. The IRRI-bred hybrids also have a yield advantage over other marketed hybrids; for instance, in 2011, 3 to 14 hybrids released in the Philippines were from IRRI, and the average yield of the 3 hybrids was 6.93 t/ha, which was 6.51% higher than the average yield of the other 11 hybrids developed by other institutes or seed companies (data source: National Collaborative Testing organized by the Department of Agriculture and PhilRice). IRRI has also been keeping a continuous and increased supply of hybrid rice breeding lines and parents for national and private partners. Since the HRDC began in 2008, the number of hybrid rice breeding lines shared with partners has increased annually and it reached more than six fold in 2012 compared with what IRRI shared in 2005 (Fig. 2).

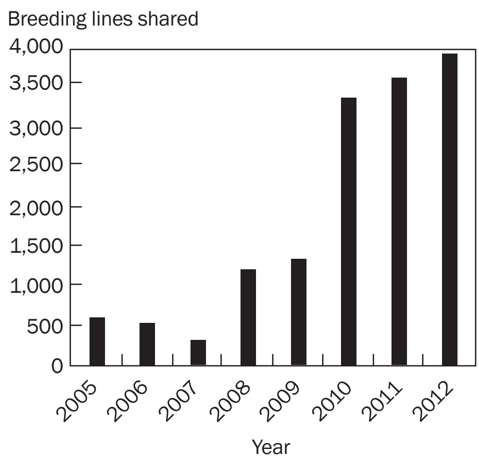

Fig. 2. IRRI hybrid rice germplasm shared with partners.

The average yield heterosis over inbred varieties in the tropics is only about 9% (Peng et al 1999), less than the heterosis realized in temperate rice regions such as China, the United States, and South America, where yield heterosis is a minimum of 15%. The heterotic response of parents with different genetic backgrounds has been a puzzle for hybrid rice breeders for a long time. IRRI-bred hybrid rice materials have been widely employed in national and private organizations for developing hybrids, but the germplasm shared has insufficient information on genetic background, diversity, and heterotic groups necessary for breeding heterotic hybrids. The lack of genetic information on hybrid rice parents could be one of the main reasons for the low yield heterosis in the tropics because hybrids are produced with unknown genetic diversity and population structure.

To tackle the issue of heterotic groups and patterns, a SKEP project sponsored by Pioneer Overseas Corporation in 2009 started to study genetic diversity and heterotic groups for IRRI-bred hybrid rice parents. A total of 168 hybrid rice germplasm accessions historically developed at IRRI were genotyped with 207 simple sequence repeat(SSR) markers and further confirmed with single nucleotide polymorphism(SNP) markers (He et al 2012). Based on the parental groups generated from marker data, hybrids were made among selected sampling parents within and between groups, and evaluated in five environments for yield and yield heterosis, and other agronomic traits. The major findings and conclusions from the study follow:

1. Six subgroups within two major groups were formed for IRRI-bred hybrid rice germplasm, and the clusters for the majority of the parental lines were in accordance with the parental pedigree information (Fig. 3).
2. Cytoplasmic male sterile (CMS) B and R lines were clearly separated into different clusters by SSR markers, but some B lines showed a high degree of allelic sharing with R lines and were clustered into the R-line group, which means those B lines were developed more genetically related to the R lines (Fig. 3).
3. Genetic divergence within each category of B and R lines has similar values, indicating similar genetic diversity within each parental group.

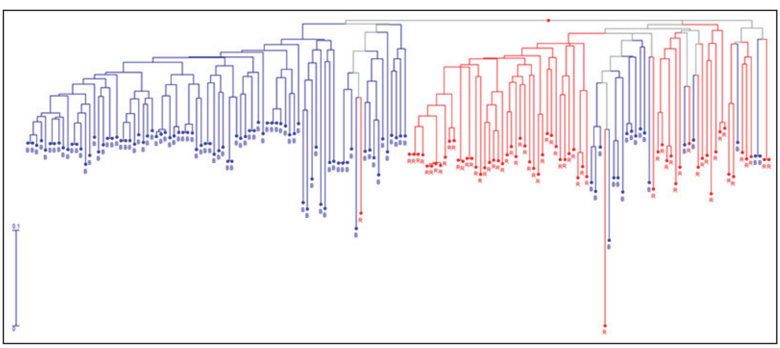

Fig. 3. Cluster of 168 IRRI hybrid rice parents based on C.S. Chord genetic distance generated from 207 SSR markers (blue = B lines and red = R lines).

4. Yields of parents and hybrids differed significantly over environments (significant G × E interaction); therefore, it is difficult to develop a "universal good-performing" product.
5. Four possible heterotic patterns are preferred for the IRRI-bred hybrid rice germplasm, represented by G5 (IR68280B, IR72795B, IR73323B) and G6 (IR58025B, IR79156B, IR80151B) in female parental pools and G2 (IR64R, IR72102-4-159-1-3-3R, IR72998-78-1-3-2R) and G3 (IR69712-154-2-3-1-3R, IR71921-4B-B-23-2-1R, IR73971-87-1-1-1-1) in male parental pools, and the hybrids made from these heterotic pools could give the best yield and yield heterosis (Fig. 4).
6. The B lines (all lines in G1) clustered in the R-line group do not contribute much for producing heterotic hybrids, and they could be "cleaned up" from the parental pools.
7. Breeding programs for B and R lines should be separated to maximize genetic diversity, and share common ancestors as little as possible.
8. Combining ability and genetic diversity are the two priorities and prerequisites for breeding hybrid parents.
9. The association of yield heterosis and parental diversity based on markers could be enhanced when parents are first grouped by markers.

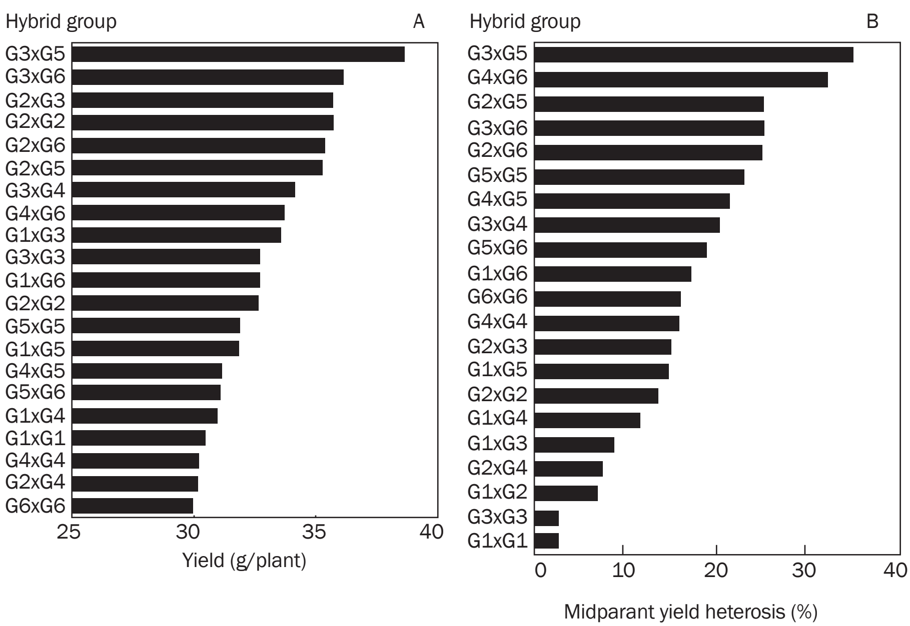

Fig. 4. Yield (A) and mid-parent yield heterosis (B) of hybrids from different heterotic groups.

Improving the yield of hybrid seed production

A major research effort at IRRI recently is to increase the yield of hybrid rice seed production through improving flowering traits for high outcrossing in female parents. Twenty-nine new CMS lines with improved seed yield have been developed since 2008. Some of these new CMS lines even have similar seed set as their corresponding CMS B lines and with natural outcrossing as high as 60% or more. These new CMS lines are being advanced for producing more seeds and testing for combining ability.

The development of new CMS lines with high outcrossing is always a high research priority in the hybrid rice breeding group. In every season, we make new crosses and select breeding lines from hybrid and inbred rice breeding programs to test their male sterility maintenance and screen for high outcrossing. More than 400 pairs of new A × B pairs with various genetic backgrounds are being evaluated or advanced in each crop season. The targeted traits for selection are large-size stigma with high exsertion and normal flowering behavior that enhance outcrossing.

Ongoing hybrid rice research using molecular technology at IRRI

SSR and SNP markers are being used routinely in hybrid rice research and breeding, mainly in screening of genetic diversity and marker-assisted backcrossing (MAB), focusing on the following areas:

- Germplasm accessions and new breeding lines are routinely screened for genetic diversity using SNP markers.
- The large-size stigma from wild rice is being genotyped, phenotyped, and transferred into hybrid rice female parents.
- Various *Xa* genes (resistance to bacterial leaf blight) are being integrated into existing hybrid rice parents using MAB.
- QTLs for drought tolerance were integrated into hybrid rice parents using MAB, and rice hybrids with and without drought-tolerance QTLs are being evaluated for yield performance.
- Submergence-tolerance (*SUB1*) genes are being integrated in hybrid rice parents.
- SSR markers for WA (wild abortive) CMS male fertility restoration (*Rf3* and *Rf4*) are being converted into SNP markers.

Progress in hybrid rice development

In addition to supporting the hybrid rice breeding program at IRRI, the HRDC has sponsored and organized the following major activities:

- Annual meetings. Scientists from IRRI and other organizations were invited to present progress in rice and hybrid rice research, and introduce new research and production technologies. The meetings among the HRDC members facilitate communication among the hybrid rice research community and between the public and private sector, receive feedback for requests and demand for further research on and strategies for inbred and hybrid rice, and provide advice for policymakers.

- Hybrid rice yield trials in multiple environments. Sponsored by HRDC members, IRRI organizes a hybrid rice yield trial in multiple locations for HRDC members. Experimental hybrids from HRDC members are collected and distributed to the HRDC trial sponsors for evaluation at locations where the members have the most interest. Data are collected following a standard protocol and then analyzed and published for all HRDC members. Some 40–50 hybrids are tested annually at 10–12 locations in both dry and wet seasons. The yield trial lets members gain performance information on their products at locations where they have interest, but may have difficulty to carry out trials by themselves. The locations selected cover countries in South and Southeast Asia. One lesson learned from the yield trials is that the adaptation of hybrid rice to the local environment and rice ecosystem is critical for a rice hybrid to grow successfully. A superior hybrid growing well in one location may fail to perform as expected in another location if it does not fit the new environment, even though it is a "super high-yielding" hybrid rice. Significant G × E interaction makes it difficult to breed a product that fits both the dry and wet season in the tropics.
- Training for hybrid rice breeding and seed production. In collaboration with the Jiangxi Academy of Agricultural Sciences, the HRDC has organized training on hybrid rice breeding and seed production for HRDC members in the last 3 years, with a total of 28 trainees. The training is based on full cost recovery and funded by members themselves with a partial subsidy from the HRDC. Young scientists and technicians are trained in classroom lectures, hands-on practice, and field tours of breeding and seed production bases as well as seed enterprises involved in the hybrid rice seed business.
- A hybrid rice impact study. To assess the farm-level impacts and key challenges of hybrid rice adoption, a study sponsored by the HRDC was carried out in 2008 in selected states of India (Janaiah and Xie 2010). Productivity gains and the financial profitability of commercial cultivation of hybrid rice were analyzed in side-by-side comparisons, and the economic aspects of hybrid rice seed production were investigated. A survey showed that the new generation of rice hybrids has considerably outperformed existing inbred rice varieties in yield gain and profitability in eastern India, and there has been a considerable improvement in grain quality and consumer acceptance. Hybrid rice seed production would not be a constraint to the large-scale adoption of acceptable hybrid rice as F_1 seed production is highly profitable for seed producers. The key challenges for hybrid rice R&D, however, are the development of new rice hybrids with competitive and comparable grain quality, wider adaptability, and suitability for irrigated areas; a further increase in yield potential; and a reduction in the retail seed price.

With strong support from the HRDC, IRRI will strengthen its ability and capacity in hybrid rice R&D to contribute more for rice research and production.

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The development of hybrid rice in India: a transformation toward improved grain quality with enhanced yield gain

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Since the mid-1960s plant type-based high-yielding varieties have been developed and released, which brought a quantum jump in production and productivity. But for their acceptance and spread, grain quality has become an important criterion after yield. Consumers base their concept of quality on grain appearance, size and shape, behavior upon cooking, taste, tenderness and the flavor of cooked rice. Cooking quality preferences vary within a country, within ethnic groups, from one country to another and within different geographic regions (Juliano et al 1964). A change in income level and self-sufficiency-induced rice availability for consumption has brought a shift in consumers as well as market preferences for better rice grain quality. As good grain quality gives higher returns to farmers, it has now become very important to incorporate quality features in a desirable range into conventionally bred varieties as well as in hybrids for their adoption. As the grains harvested from commercial rice hybrids denote F_2 generation produce and differ in characters, developing hybrids with acceptable grain quality to meet consumer preferences is a challenging objective that has a bearing on the adoption of this technology. The major components of rice grain quality are (1) milling quality; (2) grain size, shape and appearance and (3) cooking and eating quality.

Milling quality

Milling recovery is one of the most important criteria of rice quality, especially from a marketing perspective. Milling recovery of rough rice is an estimation of the quantity of head rice and total milled rice that can be produced from a unit of rough rice, expressed as a percentage. A variety should possess a high turnout of whole grain (head) rice. Milling recovery depends on grain shape and appearance, which has a direct effect on the percentage of hulling, milling, and head rice recovery. Normally, the hull content is 20–22% of the rough rice. Shobha Rani et al (2003) studied the hull content in different varieties, which ranged from 14% to 28% of grain, in an attempt to select for lower hull weight to improve milling and head rice yields in aromatic basmati varieties. Bran and embryo account for 8% to 10% of the rice grain. Thus, for a given sample of rice, about 70% milled rice is obtained. The quantity of whole rice obtained is known as head rice recovery (HRR) and is expressed as a percentage of rough rice. For a sample of 100 grams (g) of rough rice, 70 g of milled rice is obtained and if 20 g are broken, the head rice recovery is 50%. Head rice recovery may vary from as low as 25% to as high as 70% depending on several factors.

Head rice recoverability is an inherited trait, although environmental factors such as temperature and humidity during ripening and post harvest are known to influence grain breakage during milling. Grain size and shape, hardness, the presence or absence of abdominal white which also referred as grain chalkiness, moisture content, harvest precision, storage conditions, processing, and type of mills employed have a direct bearing on head rice recovery (Bhattacharya 1980). In general, varieties with long or long bold grains and those having white centers give lower head rice yields. Varieties possessing medium slender, long slender, and translucent grains give high head rice yields. Parboiling increases milling percentage. Varieties with high protein content also suffer less breakage. Sun cracking, which is caused by alternate drying and wetting of grains due to delayed harvest also leads to more breakage of grain. High gelatinization temperature types are less prone to cracking. Breeders have to pay special attention to improving this trait, as rice outturn is the most important index for the fixation of procurement price for paddy.

The full advantage of the high yield ability of hybrids cannot be realized unless hybrids exhibit milling quality equal to or higher than that of either parent or the commercially accepted standard check variety. Low milling recovery was one of the significant deficiencies of rice hybrids when introduced from China in the U.S. according to Rutger and Bollich (1985). They attributed this problem to the cytoplasmic male sterile (CMS) lines. Although, in the initial years, some of the experimental hybrids recorded low HRR (Table 1), studies have shown that hybrids with higher HRR can be obtained when the parents are selected carefully. If the parents are prone to considerable breakage on milling, the F_1 would normally record lower HRR than the parents. A majority of the released hybrids were not upto the mark for this trait, mainly because the genetic base of the female parent in most cases had been narrow, mainly involving only two CMS lines, IR58025A and IR62829A, which have low HRR (Table 2). With the development and use of new CMS lines, improvement in this trait is increasingly evident, with many recently tested experimental hybrids exhibiting high head rice yields (Shobha Rani et al 2002). Thus, of the 381 experimental hybrids tested, 131 recorded >60% head rice yields (Fig. 1A) and some promising entries were TNRH 173, MTUHR 2093 and JKRH 3333 with HRR ranging from 62.2% to 65.3% (Table 3). Among the released hybrids (2001-12), mention can be made of DRRH 3, PRH 122, CORH 3, GK 5003 and NK 5251 which recorded high head rice ranging from 60% to 70% (Table 4) compared with the hybrids released in the previous decade, which had HRR of 45% to 60%. Therefore, to improve this parameter in hybrids, it is essential to choose parents with high head rice percentage, especially in restorers and this should not be a problem given the wide choice of restorers and new CMS lines now available in hybrid rice breeding programs.

Table 1. Quality characteristics of some released hybrids, DRR, Hyderabad, 1991-2000.[a]

Hybrid	Year	Hull (%)	Mill (%)	HRR (%)	KL (mm)	KB (mm)	L/B ratio	Grain type	KLAC (mm)	ER	WU (mL)	VER	ASV	AC (%)
APHR-2	1994	76.6	67.8	55.9	6.2	2.1	2.9	LS	10.2	1.6	260	3.8	2.5	27.8
CNRH-3	1995	77.6	70.3	51.7	5.8	2.3	2.6	MS	10.9	1.9	220	4.5	3.5	27.5
CORH-2	1998	79.0	70.9	48.0	5.9	2.3	2.6	MS	11.3	1.9	355	4.7	4.1	25.9
DRRH 1	1996	77.5	67.8	54.0	6.8	2.1	3.3	LS	11.3	1.7	208	5.3	5.2	22.4
KRH-2	1996	77.6	67.3	57.3	6.1	2.2	2.8	LS	12.3	2.0	203	4.7	5.0	20.9
ADTRH-1	1998	79.1	70.9	48.8	6.6	2.1	3.2	LS	11.4	1.7	240	5.0	5.1	24.5
PHB-71	1997	79.7	71.3	58.6	6.5	2.1	3.1	LS	12.4	1.9	223	4.7	6.0	22.8
NSD-2	1998	78.3	70.5	46.2	6.6	2.2	3.0	LS	11.7	1.8	238	5.0	6.1	21.2
PSD 1	1997	80.1	67.6	50.0	6.43	1.80	3.57	LS	–	–	245	5.3	7.0	18.1

[a] Hull = hulling; Mill = milling; HRR = head rice recovery; KL = kernel length; KB = kernel breadth; L/B ratio = length/breadth ratio; KLAC = kernel length after cooking; ER = elongation ratio; WU = water uptake; VER = volume expansion ratio; ASV = alkali spreading value; AC = amylose content; GC = gel consistency.

Table 2. Performance of A lines for key quality characters.[a]

A line	HRR (%)	KL (mm)	L/B ratio	Grain type	ASV	AC (%)	GC (mm)
IR58025A	55.3	6.20	3.57	LS	6.5	18.7	86
IR62829A	40.2	5.69	2.89	MS	2.0	24.0	94
IR68886A	41.5	6.03	3.13	LS	2.0	27.1	86
IR68888A	28.7	5.84	3.07	MS	5.3	26.6	76
IR68897A	36.0	6.29	3.25	LS	7.0	26.3	78
IR69628A	37.5	5.80	2.96	MS	4.3	14.8	37

[a]HRR = head rice recovery; KL = kernel length; L/B ratio = length/breadth ratio; ASV = alkali spreading value; AC = amylose content; GC = gel consistency.

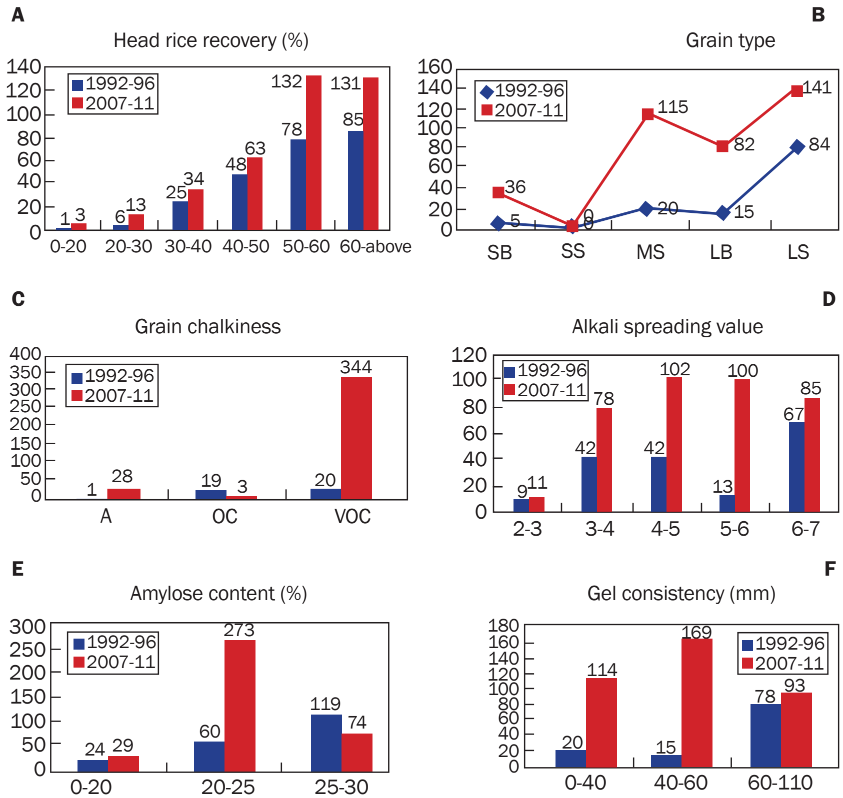

Fig. 1. Performance of rice experimental hybrids for different quality parameters, DRR, Hyderabad.

Table 3. Experimental hybrids possessing desirable grain, milling, and cooking quality traits.[a]

Experimental hybrid	Hull (%)	Mill (%)	HRR (%)	KL (mm)	KB (mm)	L/B ratio	Grain type	Grain chalk	VER	WU (mL)	KLAC (mm)	ER	ASV	AC (%)	GC (mm)	Aroma
ARRH 7434	80.9	71.7	53.6	6.55	1.99	3.29	LS	VOC	5.3	340	10.5	1.60	5.2	22.64	70	NS
VNR 202	78.3	70.2	55.8	5.65	2.24	2.52	MS	VOC	5.6	275	10.7	1.89	4.8	21.69	58	NS
HRI 164	81.8	73.1	54.9	6.51	2.06	3.16	LS	VOC	4.6	295	10.1	1.55	4.8	21.61	60	NS
TNRH 173	78.4	68.9	65.3	5.67	1.99	2.84	MS	VOC	5.5	225	8.7	1.53	5.2	21.47	58	NS
TNRH 174	79.9	69.6	59.9	5.54	1.96	2.83	MS	VOC	4.7	270	9.0	1.62	5.0	24.24	63	NS
KPH 56	80.8	72.0	52.6	6.16	2.01	3.06	LS	VOC	5.5	305	9.6	1.55	5.2	24.08	50	NS
MTUHR 2093	77.8	69.3	64.4	5.12	1.91	2.68	MS	VOC	5.3	230	8.4	1.64	5.2	24.58	59	NS
MTUHR 2094	78.2	67.1	54.6	4.89	1.85	2.61	MS	VOC	5.3	270	8.6	1.75	5.0	24.71	60	NS
27P11	79.7	70.4	56.4	5.08	1.87	2.72	MS	VOC	5.6	285	8.6	1.69	5.0	24.41	30	NS
JKRH-1230	79.5	70.5	59.6	5.17	2.06	2.51	MS	VOC	5.6	215	9.1	1.76	5.0	23.94	49	NS
JKRH-3333	80.5	72.3	62.2	5.17	2.06	2.51	MS	VOC	5.3	185	9.1	1.76	4.0	24.39	47	NS

[a] Mill = milling (%); HRR = head rice recovery (%); KL = kernel length (mm); KB = kernel breadth (mm); L/B = length/breadth ratio; WU = water uptake (ml); ASV = alkali spreading value; AC = amylose content (%); GC = gel consistency; grain chalk = grain chalkiness; VER = volume expansion ration; VOC = very occasionally present; NS = nonscented; LS = long slender; LB = long bold; MS = medium slender; SB = short bold.

Table 4. Released hybrids possessing desirable quality traits, DRR, Hyderabad, 2001-2012.[a]

Hybrid	Year	Mill (%)	HRR (%)	KL (mm)	KB (mm)	L/B ratio	Grain type	ASV (%)	AC (%)
PRH 122	2001	74.5	68.5	6.79	2.09	3.24	LS	4.4	21.6
Suruchi	2004	72.0	68.0	5.38	2.0	2.69	MS	5.3	23.6
DRRH 2	2005	73.0	63.0	6.50	1.92	3.4	LS	6.5	25.5
CORH 3	2006	68.2	60.3	6.50	2.20	2.95	MS	4.0	21.7
GK 5003	2008	73.0	68.0	6.30	1.85	3.30	LS	4.0	24.3
DRH 75	2009	73.9	64.7	6.60	1.95	3.38	LS	5.0	24.5
HRI 157	2009	71.0	65.0	6.15	2.22	2.76	LB	4.5	24.0
DRRH 3	2009	71.7	67.3	5.28	2.00	2.64	MS	4.0	23.8
US 312	2010	70.0	68.0	6.10	2.02	2.95	MS	5.0	23.1
Indam 200-017	2010	72.3	58.9	6.13	2.27	2.69	LB	5.5	24.3
27P11	2011	72.2	62.0	5.22	1.82	2.87	MS	5.0	24.3
NK 5251	2012	72.1	69.1	6.00	1.96	3.06	LS	5.0	23.2

[a] Mill = milling; HRR = head rice recovery; KL = kernel length; KB = kernel breadth; L/B ratio = length/breadth ratio; ASV = alkali spreading value; AC = amylose content.

Grain size, shape, and appearance

The appearance of milled rice is important to consumers, which in turn makes it important to producers and millers. Thus, grain size and shape are the first criteria for rice quality that breeders consider in developing new varieties for release for commercial production (Adair et al 1966). Preferences for grain size and shape vary from one group of consumers to another. Some ethnic groups prefer short bold grains, while medium and long slender grains are prized by others.

Length of the grain is more variable and important than width and thickness or shape. Bold grains give low head rice recovery because of high breakage. Short to medium slender grains break less than long grains during milling. Thus, grain size and shape have a direct effect on the yield of head rice. Grain length and shape are independently inherited. Some of the grain tissues are maternal in origin and some result from the fertilization of genetically diverse gametes. The lemma and palea of the rice hull are maternal tissues. Seed size and shape are determined by the shape and size of hulls. Since genetic segregation for shape and size of hulls for spikelets borne on F_1 plants does not occur, all F_2 seeds have similar dimensions even though the parents may be diverse in size and shape (Khush et al 1986). In general, the length and shape of F_1 grains are intermediate to those of the parents. In a study of 27 hybrids tested at the Directorate of Rice Research, Hyderabad 17 belonged to long slender, 4 to long bold, 5 to medium slender and 1 to short bold grain type. It was notable that four among the long slender were extra long type (Rani et al 1998). Therefore, to develop medium grain hybrids, hybrid parents possessing long and short grains can be used. But, to develop long-grain hybrids, both parents must have long slender grains. As the grain preference in the Indian subcontinent is in general for long slender and medium slender types, of the 624 experimental hybrids tested, the highest number (175) were long slender, followed by 135 medium slender-grain hybrids (Fig. 1B).

Standards for the evaluation of grain length and shape of breeding materials vary among countries and marketing areas. The government of India appointed the Ramaiah Committee in 1965 to recommend a uniform standard of grain classification. The committee suggested a more rational classification consisting of five groups, based on length and length/breadth ratio of the kernel (Table 5). A similar international classification was also developed by the International Rice Research Institute, Philippines (IRRI 1996).

Consumers prefer white translucent grains and pay a premium for them. Grain appearance is largely determined by endosperm opacity, the amount of chalkiness. Based on endosperm opacity, the rice endosperm is classified as waxy or nonwaxy. Waxy rice is devoid of or has only traces of amylose content and is opaque. Nonwaxy rice has varying amylose content (2.1% to 32%) and is dull, hazy, or translucent. Further, the endosperm is a triploid tissue formed by the fusion of one male nucleus and two female nuclei (polar nuclei). If the parents vary in endosperm appearance, the F_2 grains show clear segregation and may pose a problem in hybrids. Waxy and low amylose rice with dull endosperm is not preferred in India. Chalky white spots, which often appear in the starchy endosperm, lower the market value of the variety. In some varieties, the grain tends to break more frequently in these chalky portions or pits left by the embryo when it is milled. The starch granules in the chalky areas are less densely packed than those in translucent areas (Del Rosario et al 1968) and there are air spaces between the starch granules. Therefore, the chalky areas are not as hard as the translucent areas and the grains with chalkiness are more prone to breakage during milling. In an earlier study of 130 parental lines and hybrids scored for grain chalkiness, 34% of the lines were fully chalky, 50% showed occasional chalkiness, and 14% were devoid of any. Screening of experimental hybrids during 2007-11 showed that a maximum of 344 hybrids showed very occasional grain chalkiness, which indicates a positive improvement of hybrids with respect to grain appearance (Fig. 1C). The heritability of this character seems to be low, because of the various agronomic practices and preharvest handling, together with other maturity factors, are found to influence the expression of chalkiness to some extent (Kaul 1970). However, by selecting suitable parents, developing hybrids without any chalky spots would not be a difficult objective to achieve.

Table 5. Systematic classification of rice (Ramaiah classification).

Long slender (LS)	Length 6 mm and above, length/breadth ratio 3 and above
Short slender (SS)	Length less than 6 mm, length/breadth ratio 3 and above
Medium slender (MS)	Length less than 6 mm, length/breadth ratio 2.5 to 3.0
Long bold (LB)	Length 6 mm and above, length/breadth ratio less than 3
Short bold (SB)	Length less than 6 mm, length /breadth ratio less than 2.5 mm

Source: Rice Research in India, ICAR 1985.

Cooking and eating characteristics

Cooking and eating characteristics are largely determined by the properties of the starch that makes up 90% of milled rice. Gelatinization temperature (GT), amylose content (AC), and gel consistency (GC) are the important starch properties that influence cooking and eating characteristics. A complex relationship, however, exists between chemical characters and quality.

Gelatinization temperature

Gelatinization temperature is a physical property of the starch present in rice and it refers to the range of temperature within which starch granules start to swell in hot water. Thus, GT determines the time taken to cook the rice. Unmodified starch granules are generally insoluble in water below 50 °C. When starch granules are heated in water beyond a critical temperature, the granules absorb a large amount of water and swell to many times their original size. Over a critical temperature range, the starch granules undergo an irreversible process known as gelatinization, which is marked by crystalline melting, loss of birefringence and starch solubilization. If we cook rice at a temperature below the critical gel temperature of the starch, the viscosity is low. However, as soon as the temperature rises above the GT, the starch granules begin to swell and viscosity increases. The temperature at the onset of this rise in viscosity is known as the pasting temperature. The pasting temperature provides an indication of the minimum temperature required to cook for a given rice sample. GT ranges from 55 to 79 °C. Environmental conditions such as temperature during grain development influence GT. A high ambient temperature during grain ripening results in starch with higher GT (Dela Cruz et al 1989). GT of rice varieties can be classified as low (55 to 69 °C), intermediate (70 to 74 °C) and high (> 74 °C).

Estimation of GT is indexed by the alkali digestibility test (Little et al 1958). It is measured by alkali spreading value (ASV). The degree of spreading value of individual milled rice kernels in a weak alkali solution (1.7% KOH) is very closely correlated with GT. Rice with low GT disintegrates completely, whereas rice with intermediate GT shows only partial disintegration. Rice with high GT remains largely unaffected in the alkali solution. In breeding program, the ASV technique is used extensively for estimating GT. GT and cooking time of milled rice are positively correlated (Juliano et al 1964). Rice with high GT takes a longer time to cook than do low-GT types. On the contrary, Bhattacharya and Sowbhagya (1971) observed that water uptake and cooking time are strongly influenced by the size and shape of rice grain and only marginally by GT. GT does not correlate with the texture of cooked rice. GT is not associated with other important plant or grain traits except for certain useful correlations with AC (Jennings et al 1979). Varieties with low GT generally have low AC. The quality and quantity of starch and GT strongly influence the cooking quality of rice (Ghosh and Govindaswamy 1972). GT affects water uptake, volume expansion and linear kernel elongation (Tomar and Nanda 1985). Rice varieties with intermediate GT are preferred and mostly basmati varieties and nonbasmati varieties of good quality for table purposes have intermediate GT. Earlier studies have not given a clear picture regarding inheritance pattern. However, reports on the involvement of dominant and additive (Hseih and Wong 1988), digenic (Stansel 1966), and polygenic (Puri and Siddiq 1980) mode of inheritance for this trait are available. The gelatinization behavior of starch granules in rice is predominantly determined by amylopectin structure (Lanceras et al 2000). The mechanism underlying the synthesis of amylopectin is highly complicated.

In a hybrid program, hybrids with low GT were obtained when both parental lines had low GT, while intermediate-GT types were derived when intermediate × intermediate and intermediate × high-GT types were used. As grain size and shape do not normally differ in hybrids, it appears that when a bulk sample of low and intermediate GT grains are cooked, low-GT grains cook first and release heat and water, which affects the cohesiveness of cooked rice. Segregation is not desirable, as high-GT types remain undercooked and hence not preferred. Therefore, to isolate hybrids with intermediate GT, it is important to select especially a male parent with intermediate GT as the two widely used CMS lines IR62829A and IR58025A have high- and low-GT values (Shivani et al 2002). Emphasis is not on heterosis for this trait as desirable grain types are those possessing intermediate GT, which again underlines the need for a careful choice of parents. In the earlier study with 173 hybrids indexed for GT, only 55 entries showed a desirable intermediate value. It is encouraging to note that of the 376 experimental hybrids analyzed during 2007-11, a maximum of 202 possess desirable GT values (Fig. 1D).

Amylose content

Amylose content (AC) is considered as the single most important character for predicting rice cooking and processing behavior (Juliano 1979, Webb 1985). Many of the cooking and eating characteristics of milled rice are influenced by the ratio of amylose and amylopectin in the rice grain (Juliano et al 1964). Amylose is the linear fraction of starch in non-glutinous varieties, whereas amylopectin, the branched fraction, makes up the reminder of the starch. Amylose content correlates negatively with taste panel scores for cohesiveness, tenderness, color and gloss of rice. Amylose is almost absent from waxy (glutinous) rice. Such rice does not expand in volume, is glossy and sticky and remains firm when cooked (Juliano 1979). This rice is the staple food of people in northern Thailand and Laos.

High-amylose rice shows high volume expansion and a high degree of flakiness. It cooks dry, is less tender and becomes hard upon cooling. All of the japonica varieties of temperate regions have low AC. Varieties grown in the Philippines, Malaysia and Indonesia have intermediate AC. Both intermediate and high-amylose types are commonly grown in the Indian sub-continent and the preference is for the former types. Intermediate-amylose rice cooks moist and tender and does not become hard upon cooling. Rice varieties are grouped on the basis of their AC into waxy (0–2%); very low (3–9%), low (10–19%), intermediate (20–25%), and high (>25%). Intermediate-amylose rice is the preferred type in most of the rice growing countries of the world except where low-amylose japonicas are preferred.

Studies on the inheritance of AC have shown the involvement of one major gene and several modifiers with high AC incompletely dominant over low AC (Chauhan and Nanda 1983). Kumar and Khush (1986) reported complete dominance of high AC over those types with low and intermediate AC. The influence of genes with minor effects or modifiers was also noted. Their study indicated that the mean AC of F_2 bulk seed samples was between that of the parents in many crosses and the more the parents differ the more is the difference in the F_2 seeds. But, several workers have reported that hybrids between low- and high-amylose parents show intermediate amylose content. Instances of medium and low amylose parents showing transgressive segregation toward high amylose content were also experienced, indicating that the inheritance pattern of AC may vary according to the cross. Hence, to develop hybrids with appropriate AC, depending on regional preferences, suitable parents should be selected so that uniformly cooked rice with desirable flakiness, tenderness and cohesiveness is achieved. Among CMS lines, the most widely used (IR58025A and IR62829A) possess low and intermediate AC, respectively. In a study of 203 experimental hybrids, 60 entries (29.5%) recorded intermediate AC. But, when 376 hybrids were analyzed for AC during 2007-11, 273 (72.6%) showed desirable intermediate AC thus, showing remarkable improvement in capturing intermediate AC, which denotes good cooking quality (Fig. 1E). Some of the released hybrids with good cooking quality are DRRH 3, PRH 122, CORH 3, GK 5003 and NK 5251 (Table 2).

Amylose content is controlled by the *Waxy* gene encoding granule-bound starch synthase (GBSS I). Studies on the inheritance of AC have shown the involvement of one major gene and several modifiers with high AC, incompletely dominant over low AC (Chang and Li 1981, Chauhan and Nanda 1983). In addition to the *waxy* gene, the involvement of two complementary genes was also reported (Stansel 1966). A difference in AC was observed due to the dosage of amylose genes in the endosperm (Kumar and Khush 1986) but AC was not directly proportional to the number of W_x doses (Okuno 1978). Based on the GBSS I enzyme quantity accumulated during the process of grain filling, three alleles (*wx, Wx^a*, and *Wx^b*) have been identified for the *waxy* gene in sticky rice and indica and japonica types respectively. However, the *Wx* locus alone was not enough to explain all the observed AC variation among rice cultivars and some minor genes might also be involved. Rice breeders can use waxy SSR and CT-SSRs together with G-T SNP to develop rice varieties with a desirable range of AC.

Gel consistency

The main factor that determines the texture of cooked rice is amylose content. However, cohesiveness, tenderness, color and gloss differ greatly based on gel consistency (GC) when AC is high. Varietal differences in GC exist among varieties of similar AC (>25%). The GC test is based on the consistency of the rice paste and differentiates among varieties with high AC. The test separates high-amylose rice varieties into three categories: soft, medium and hard. Varieties with soft GC are preferred as the cooked rice would be more tender. GC of rice is normally soft when AC is less than 25%.

In a study of a cross between high- and low-GC parents, a single major gene was reported to control this character with high GC being dominant (Chang and Li 1981). In the bulk F_2 samples of hybrids involving high-, intermediate, or low-GC parents, Khush et al (1986) observed positive and negative heterosis depending on the specific combinations. In some cases, the hybrids possess hard GC even in soft × soft combinations, indicating the influence of modifiers in the expression of this trait. Heterosis in a negative direction is not preferable, as it would result in the identification of hard-GC types. Positive heterosis resulting in medium and soft GC is desirable. It is also advisable to use female parents with medium GC to obtain hybrids with desirable values for this trait. In a study of 130 CMS lines, restorers, and experimental hybrids, 78 genotypes recorded soft GC and 13 among them were experimental hybrids. At DRR, investigations into GC involving 113 (1992-96) and 367 (2007-11) experimental hybrids revealed that, over the years, improvement is more toward medium GC (Fig. 1F).

Earlier genetic studies revealed that GC follows monogenic inheritance (Chang and Li 1981). However, the involvement of one major gene plus several minor genes has also been reported (Tang et al 1989). It has also been observed that AC is highly negatively correlated with GC hence, the improvement of both quality traits simultaneously becomes difficult (Chang and Li 1981). Recent QTL mapping confirmed the presence of a locus controlling GC on chromosome 6 (Huang 2004). But, up to now, no perfect marker has been reported for this trait therefore, the identification of tightly linked molecular markers for GC will help breeders in tracking the flow of soft GC locus in breeding material, which in turn will be helpful in precision breeding for this trait.

Aroma

Rice aroma plays an important role in its consumer acceptability and it draws a premium price in certain specialty markets (Shobha Rani 1992). The scent of aromatic rice is a highly heritable trait and is reportedly under the control of a single recessive gene (Sood and Siddiq 1980 and several other workers). Initially, Ahn et al (1992) mapped a fragrance gene (*fgr*) on chromosome 8 and identified a marker at a genetic distance of 4.5 cM. Bradbury et al (2005a) suggested that eight bp deletions and three SNPs on exon 7 of betaine aldehyde dehydrogenase 2 (*badh2*) were the likely cause of the fragrance in jasmine and basmati types of rice. More than 100 compounds that contribute to rice aroma have been identified (Widjaja et al 1996). The popcorn-like smell of aromatic rice stemming primarily from its 2-acetyl-1-pyrroline (2-AP) content is considered desirable by many consumers (Buttery et al 1983). As many compounds are responsible for fragrance apart from 2-AP, there is a strong possibility of the presence of allelic and gene diversity for these fragrant compounds (Sakthivel et al 2007, Muralidhara Rao et al 2007).

India is home to thousands of aromatic rice types, including the unique long-grain basmati types, which have excellent grain elongation on cooking. On account of these special qualities, the country has a monopoly in exporting basmati rice and it earned as high as about US$19 billion in 2008-09. Therefore, many efforts have been made to develop hybrids that can give higher yield and retain basmati quality features. At IARI, New Delhi, in addition to converting Pusa Basmati 1 into a basmati CMS line named Pusa 3A, a number of basmati restorers have been developed and most of these lines are isocytoplasmic in nature (Virmani and Zaman 1998). Grain elongation appears to be a quantitative trait. Preliminary experience indicates that only a few hybrid lines approach the parents in degree of elongation. To breed basmati hybrids, both parents need to possess basmati quality traits. If aromatic rice hybrids are preferred, at least one of the parents must be aromatic. At present, as the most widely used CMS line

IR58025A is aromatic, many of the hybrids developed by the public and private sector possess aroma, which is not normally liked by all consumers. However, through a special restorer breeding program initiated at IARI, New Delhi, Pusa RH 10, the first super-fine-grained aromatic hybrid, has been developed. The development of a highly productive hybrid with superior grain quality is a significant achievement in hybrid rice research in India.

Variability and interrelationships among quality parameters

At DRR, a study was conducted with 381 experimental hybrids that were analyzed during 2007-11 for 11 quality parameters and a Pearson correlation coefficient was worked out to understand the association among the different quality parameters. High variability for physico-chemical parameters was observed. Good improvement of HRR from 10.3% in 2008 to 70.5% in 2011 was recorded. The hybrids developed varied from medium slender to long slender to long bold. Volume expansion ratio (VER) and water uptake (WU) varied from 4.0 to 6.0 and 135 mL to 395 mL, respectively. Kernel length after cooking (KLAC) and elongation ratio (ER) ranged from 7.6 mm to 14.7 mm and 1.27 to 2.1 respectively. AC varied from low (12.98%) to high (28.04%) and GC varied from hard to soft.

Correlations among the physico-chemical characteristics of hybrids tested under different ecosystems, including irrigated early, mid-early and medium-duration trials, revealed significant associations among them (Table 6). Milling percentage was significant and positively correlated with HRR ($r = 0.511$, $P<0.0001$), kernel length (KL) ($r = 0.239$, $P<0.0001$), and kernel length after cooking ($r = 0.3043$, $P<0.0001$), while it showed significant negative correlation with water uptake ($r = -0.202$, $P<0.0001$). Selection for high milling percentage can enhance HRR, a very important quality trait. Significant and positive associations were found among KL and length/breadth ratio (L/B ratio) (r = 0.0.8314, $P<0.0001$), WU ($r = 0.2212$, $P<0.0001$) and KLAC ($r = 0.6457$, $P<0.0001$), indicating that the simultaneous improvement of the traits is feasible and at the same time, KL was significant and negatively associated with elongation ratio (ER) ($r = -0.3237$, $P<0.0001$) and AC ($r = -0.2208$, $P<0.0001$). Asha Christopher et al (1999) and Chakraborty et al (2009) also reported significant positive correlations among KL and L/B ratio. L/B ratio was positively and significantly associated with WU ($r = 0.2443$, $P<0.0001$) and KLAC ($r = 0.4685$, $P<0.0001$) and negatively associated with ER ($r = -0.3418$, $P<0.0001$). The association between WU and ER was negative and significant ($r = -0.3234$, $P<0.0001$) while between KLAC and ER was positive and significant ($r = 0.4965$, $P<0.0001$). Elongation ratio was found to be significant and positively associated with AC ($r = 0.2157$, $P<0.0001$) while it showed a negative correlation with GC ($r = -0.2317$; $p<0.0001$). In addition, AC and GC were significantly negatively associated with each other ($r = -0.5086$, $P<0.0001$), indicating that high-AC types can have hard, medium and soft GC and hybrids with a suitable combination of these traits can be identified for retaining good cooking quality. The significant positive associations among various quality traits can be exploited for simultaneous improvement by detailed characterization of parental lines, which would help overcome quality concerns about hybrids.

Table 6. Pearson correlation coefficients among the important physic-chemical quality traits of hybrids tested over ecosystems.[a]

	HRR (%)	KL (mm)	L/B ratio	WU (ml)	KLAC (mm)	ER (mm)	AC (%)	GC (mm)
Mill (%)	**0.5105**	**0.2393**	0.1337	**-0.202**	**0.30430**	0.1066	-0.0678	-0.1178
	<0.0001	<0.0001	0.0089	<0.0001	<0.0001	0.0374	0.1865	0.0215
HRR (%)	1.000	0.0311	0.0360	**-0.3873**	0.1253	0.1210	0.0022	-0.1033
		0.5439	0.4835	<0.0001	0.0144	0.0181	0.9647	0.0437
KL (mm)		1.000	**0.8313**	**0.2112**	**0.6457**	**-0.3237**	**-0.2208**	0.1269
			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0131
KB (mm)			**-0.5610**	-0.1139	0.0997	0.1406	-0.0434	0.0475
			<0.0001	0.0261	0.0517	0.0059	0.3975	0.3548
L/B ratio			1.000	**0.2443**	**0.4685**	**-0.3418**	**-0.1471**	0.0629
				<0.0001	<0.0001	<0.0001	0.0040	0.2201
VER				-0.0252	-0.0046	-0.0130	0.0747	-0.0615
				0.6236	0.9273	0.7995	0.1453	0.2310
WU (ml)				1.000	-0.0333	**-0.3234**	-0.0770	0.0422
					0.5166	<0.0001	0.1333	0.4114
KLAC (mm)					1.000	**0.4965**	-0.0273	-0.0660
						<0.0001	0.5940	0.1983
ER (mm)						1.000	**0.2157**	**-0.2316**
							<0.0001	<0.0001
ASV							0.0718	-0.0286
							0.1617	0.5774
AC (%)							1.000	**-0.5085**
								<0.0001

Pearson correlation coefficients, N = 381; Prob > |r| under H0: Rho = 0

[a] Mill = milling (%); HRR = head rice recovery (%); KL = kernel length (mm); KB = kernel breadth (mm); L/B: length/breadth ratio; VER = volume expansion ratio; WU = water uptake (ml); KLAC = kernel length after cooking; ER = elongation ratio; ASV = alkali spreading value; AC = amylose content (%); GC = gel consistency.

Conclusions

Hybrid rice technology is likely to play a crucial role in increasing rice production in India. In 2010, through the adoption of hybrid technology on 1.3 million hectares, an additional 1.5 to 2.5 million tons were added to the country's overall rice production (Hari Prasad et al 2011). Up to now, 59 hybrids have been released in the country and after an initial setback with regard to several quality features in the 1990s, quality has improved considerably in many of the recently released hybrids.

Rice is primarily consumed as whole grain. The harvested grains from commercial F_1 rice hybrids are F_2 seeds, which show segregation for some grain characteristics, which is a matter of concern for obtaining consumer acceptance without which farmers would have little incentive to grow hybrids despite their having very high yield potential. Although three main traits of cooking quality are regularly measured, we are yet to obtain a complete understanding of these traits. Further, sensory profiling needs to be used more fully, using trained panels in an attempt to reveal other descriptors of rice quality that can be used to design new research programs aimed at improving rice grain quality (Fitzgerald et al 2009).

The major challenge in hybrid rice breeding is to ensure that heterotic rice hybrids possess grain quality comparable with if not superior to that of inbred check varieties grown by farmers. It is therefore very important to choose only those parents that have an excellent array of desirable grain quality traits; those having divergent endosperm properties should not be chosen. Hybrids will have enhanced head rice if both parents have high head rice recovery likewise to produce medium slender grain type crossing among long to medium and short-grain parents can be attempted. But, to produce long-grain basmati hybrids, both parents must have long grain. It is prudent to choose parents with intermediate cooking quality traits even though the bulk F_2 sample of different starch characteristics was reported to have posed no problem in the cooking and eating qualities of some of the hybrids. To improve visual grain manifestation and market acceptability of hybrids, parental lines with variable endosperm properties should not be crossed. There are two possible methods of breeding for quality: (1) either develop durable resistance into the parental lines having desirable quality or (2) introgress quality traits into high-yielding, biotic stress-tolerant /-resistant parental lines, or objectively breed for key quality components not easy to phenotype due to maternal influence or having a complex mode of inheritance through marker-assisted selection. There is an imminent need for molecular markers for precision breeding to obtain the desired quality traits in the parental lines of hybrids.

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Hybrid rice breeding in India

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Hybrid rice technology is a proven and viable technology to enhance rice production and productivity. After China, India is the second country in the world to successfully exploit this technology to increase rice production. With this in view, hybrid rice research is being pursued from both the strategic and applied point of view. Significant progress has been made in developing indigenous parental lines with good floral traits and better combining ability. An array of hybrids with good grain quality (Basmati type and medium slender [MS] grain type) is developed and made available to the farming community. Breeding efforts are intensified to insulate the parental lines with built-in resistance to major biotic and abiotic stresses by adopting pedigree-, backcross-, and genetic male sterility-facilitated population improvement methods. Intersubspecific hybridization is explored to develop parental lines that can help in the development of hybrids with a higher magnitude of heterosis. Efforts have been made to develop parental lines and hybrids that perform well under limited water (aerobic), saline, and alkaline conditions. Biotechnological interventions are effectively integrated into breeding efforts to speed up the processes, such as molecular tagging of fertility restorer genes for the identification of restorers, molecular mapping, and marker-assisted introgression of wide compatibility genes for the exploitation of intersubspecific heterosis, prediction of heterosis, introgression of major biotic stress resistance genes into hybrid rice parental lines, and the identification and introgression of yield-related QTLs from wild relatives.

The hybrid rice program in India was launched in 1989, through a systematic, goal-oriented, and time-bound network project with initiative from the Indian Council of Agricultural Research (ICAR), and financial and technical support from various agencies. The area planted to hybrid rice in the country during kharif 2011 was around 2 million ha (4.5% of the total rice area of 44 million ha). It is mostly cultivated in the eastern Indian states of Uttar Pradesh, Jharkhand, Chhattisgarh, and Bihar and it contributes 2–3 million tons of additional rice to the total rice production in the country.

The main objectives of the breeding program are (1) to broaden the genetic base of restorers and maintainers, (2) to increase the frequency of restorers and maintainers, (3) to improve the grain quality and outcrossing ability of parental lines, (4) to increase the magnitude of heterosis, and (5) to incorporate resistance to biotic and abiotic stresses.

One of the major challenges in self-pollinated crops such as rice is how to maximize seed yield in seed production plots. The outcrossing ability of parental lines plays an important role in enhancing seed yield. The frequency of maintainers among elite breeding material is rather low and, even among them, all are not suitable because of one or another defect. Hence, efforts were made to introduce desirable traits into promising maintainers through recombination breeding. These promising maintainers were converted into new cytoplasmic male sterile (CMS) lines through recurrent backcrossing (Table 1) and some of these lines are registered with NBPGR, New Delhi (Table 2).

All the hybrids released in the country are based on a single source of cytoplasmic male sterility, the wild abortive (WA) system. Dependence on a single CMS source in the long run may result in genetic vulnerability of hybrids to sudden outbreaks of diseases and insect pests. Keeping this in view, efforts were made to develop CMS lines with diverse cyto-sterility sources (Table 3).

To identify the maintainer line seed admixed with CMS line seed and remove such impurities requires more labor for roguing, which adds to the cost of seed production in addition to a significant reduction in the quality of hybrid seed. With this in view, molecular markers such as a mitochondrial simple sequence repeat (SSR) marker (Rajendrakumar et al 2007) and a cleaved amplified polymorphic sequence (CAPS) polymorphic between WA CMS lines and their cognate iso-nuclear maintainer lines were developed.

Genetic improvement of restorer lines

The yield heterosis of available hybrids in the country is 15–20%, which is not economically attractive enough for farmers to switch over to hybrid rice cultivation. This needs to be increased to at least 25–30% and breeding efforts intensified to develop better restorer lines by adopting pedigree-, backcross-, and genetic male sterility-facilitated recurrent selection methods.

Many promising restorers were developed and some of these lines are registered with NBPGR, New Delhi (Table 4). Even though the main purpose of the parental line improvement program is to develop restorers or maintainers to be used in hybrid development, many promising breeding lines with good per se performance and other desirable quality features were evaluated in All India Coordinated Rice Improvement Program varietal trials across the country, and a few outstanding genotypes were released as varieties for commercial cultivation (Table 5).

A genetic male sterility (GMS)-facilitated population improvement is carried out to improve parental lines. As against the quick fixation of genes during selfing

Table 1. Promising CMS lines developed.

CMS line	Days to maturity	Outcrossing (%)
DRR 4A	126	62
DRR 6A	140	59
DRR 9A	132	69
Pusa 3A	135	30
Pusa 4A	135	40
Pusa 6A	125	50
APMS 6A	105	40

Table 2. List of CMS lines registered with NBPGR, New Delhi.

Line registered	Type of material[a]	Developed by[b]
DRR 4A & 4B	WA CMS line	DRR, Hyderabad
DRR 5A & 5B	WA CMS line	DRR, Hyderabad
DRR 9A & 9B	WA CMS line	DRR, Hyderabad
DRR 10A & 10B	WA CMS line	DRR, Hyderabad
Pusa-3A	Aromatic CMS line	IARI, New Delhi
Pusa-4A	Nonaromatic CMS line	IARI, New Delhi
RTN-2A	ARC-based CMS line	ARS, Ratnagiri
RTN-4A	WA-based CMS line	ARS, Ratnagiri
RTN-5A	Disi-based CMS line	ARS, Ratnagiri
RTN-6A	Gambiaca-based CMS line	ARS, Ratnagiri

[a] WA = wild abortive, ARC = Assam Rice Collection
[b] DRR = Directorate of Rice Research, IARI = Indian Agricultural Research Institute, ARS = Agricultural Research Station

Table 3. New CMS lines with diverse cyto-sterility sources.

CMS line	Maintainer line	CMS source	Days to maturity	Outcrossing (%)
CRMS20A	Zhanghua-1	V20-B	110	30
CRMS 32A	Mirai	Kalinga-I	140	31
CRMS 35A	Tharang Song	Oryza perennis	126	11

generations of recombination breeding, genetic male sterility-facilitated recurrent selections provide opportunities for continuous recombination, accumulation of favorable genes, broadening of the genetic base, and breaking of undesirable linkages. By using IRRI-bred populations as GMS sources, four restorer populations (DRCP 101, DRCP 102, DRCP 103, and DRCP 140) and two maintainer populations (DRCP 104 and DRCP 105) were developed. Large numbers of productive segregants selected from the populations are handled by the pedigree method (Table 6). Newly bred genetically diverse parental lines with improved plant type, grain type, maturity group,

Table 4. Restorer lines of DRR, Hyderabad, registered with NBPGR, New Delhi.

Pedigree	Traits
RPHR 2	Japonica plant type with long and heavy panicles and thick, dark green leaves, strong and broad spectrum of fertility restoration with medium slender grain type, and high head rice recovery. High pollen load and 36–45 days of grain-filling period.
RPHR 12	Strong and broad spectrum of restoration, tropical japonica plant type, high rate of pollen production with medium slender grain type, tall stature with high heterotic potential, and late maturity duration.
RPHR 517	Broad spectrum of fertility restoration with good plant type, high rate of pollen production with medium slender grain type, tall stature with high heterotic potential, and late maturity duration.
RPHR 619	Strong and broad spectrum of fertility restoration. Tall stature, intermediate plant type with synchronous tillering, high pollen load, and slow leaf senescense with medium maturity.
RPHR 1005	Broad spectrum of fertility restoration with good plant type, high rate of pollen production, and good combining ability. BPT5204 derivative with short slender grain, lower panicle position, and prominent top leaves.
RPHR 1096	Broad spectrum of fertility restoration and easily observable purple basal leaf sheath and purple apiculus, high rate of pollen production, slow leaf senescense and high head rice recovery, tall stature, and intermediate plant type with late maturity duration.

Table 5. List of varieties released through parental line improvement.

Variety	Developed at
Akshaydhan Varadhan DRR Dhan-38	Directorate of Rice Research, Hyderabad
Pusa sugandh-2 Pusa sugandh-3 Pusa sugandh-5	Indian Agricultural Research Institute, New Delhi

Table 6. Gene pools of restorers and maintainers developed at DRR, Hyderabad.

Maturity group	No. of gene pools	No. of component lines added	No. of lines developed	Special attributes
Restorer gene pool				
Medium	2	22	866	Better grain quality (long slender, medium slender grains).
Medium early	2	21	754	Good restoration/maintenance ability; improved plant type traits; high outcrossing ability (stigma exsertion); multiple disease and insect pest resistance; better combining ability for yield and yield-contributing traits.
Maintainer gene pool				
Medium	1	10	460	
Medium early	1	8	510	
Total	6	61	2,590	

biotic stress resistance, and desirable floral and combining ability traits were used as component lines in hybrid rice breeding.

Fertility restoration of WA CMS is controlled by two major loci (*Rf_3* and *Rf_4*) on chromosomes 1 and 10. With the availability of the rice genome sequence, an attempt was made to fine-map and develop candidate gene-based markers for *Rf_3* and *Rf_4* and validate the developed marker system in a set of known restorer lines. Using polymorphic markers developed from microsatellite markers and candidate gene-based markers from *Rf_3* and *Rf_4* loci, local linkage maps were constructed in two mapping populations of KRH2 (IR58025A/KMR3R) and DRRH2 (IR68897A/DR714-1-2R) hybrids. QTLs and their interactions for fertility restoration in *Rf_3* and *Rf_4* loci were identified and the QTLs in both mapping populations together explained 66–72% of the phenotypic variance of the trait, suggesting their utility in developing a marker system for the identification of fertility restorers for WA CMS (Table 7) (Balaji Suresh et al 2012).

By adopting intersubspecific hybridization for indica × tropical japonica crosses, heterosis can be increased in rice hybrids from 10–15% to 25–30%. However, this approach faces a serious problem of semisterility in the hybrids derived from such crosses. The problem of hybrid sterility could be overcome by using wide compatibility varieties possessing sterility-neutralizing wide-compatibility genetic loci. In a conventional way, to identify wide-compatibility genotypes, one needs to cross them with either an indica tester (IR36) or japonica tester (Akihikari), which is a time-consuming process. A functional marker for a wide-compatibility locus (*S5* neutral allele) has been developed (Sundaram et al 2010), which can distinguish all three allelic states (i.e., indica, japonica, and neutral) at the *S5* locus (Fig. 1).

Wild species of rice are also being used in the improvement of restorer lines. Of the two major-effect yield-enhancing QTLs (*yld2.1* and *yld8.2*) mapped from an Indian accession of *Oryza rufipogon, yld2.1* was introgressed into KMR 3, a restorer line of popular hybrid KRH 2, and several introgression lines of KMR 3 with up to a

Table 7. Selection accuracy (%) for combinations of markers for *Rf3* and *Rf4* loci.

	Rf3	RG140/ pvul[2] 47.3	DRRM-RF3-6 50.0	DRRM-RF3-10	DRRM-RF-5 48.4	RM10315 44.8	RM10318 44.9
Rf4	74.7	79.5	81.0	81.0	82.6	80.2	77.2
RM6100[a]	–	–	–	–	–	–	–
TMPPR3[a]	85.2	85.4	88.4	91.9	91.9	86.2	84.8
DRRM-RF4-10	81.0	84.2	85.3	88.4	86.0	84.2	73.0
DRCG-RF4-14	86.8	86.1	89.4	91.9	91.9	87.4	75.4
DRCG-RF4-8	85.2	82.6	89.4	91.9	91.9	87.4	75.4

[a] The numbers indicated at the top are the selection accuracy (%) values of each marker in 212 restorers
[b] The Rf4-10 etc. are names of the primers designed at our Institute as per nomenclature. The primers' names are to be retained as they are.
[c] Pvuii is the restriction enzyme of *Proteus vulgaris*. This is the restriction enzyme cutting the PCR product resulting in the polymorphism between restorers and non-restorers of Rf_3 (Nas et al 2003). The restriction enzyme is used in PCR based restriction marker of Rf_3.

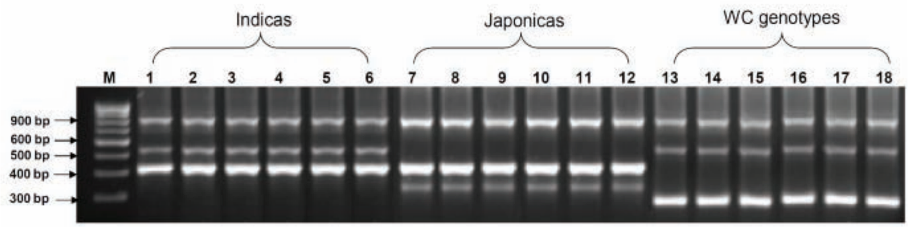

Fig. 1. The functional marker system S5-MMS can clearly distinguish all three allelic states at the S5 locus: S5-MMS can clearly distinguish genotypes possessing a neutral allele at the S5 locus (lanes 13–18) from those possessing indica (lanes 1–6) or japonica alleles (lanes 7–12) and hence is highly useful for quick identification of wide-compatibility genotypes and for predicting the success of intersubspecific cross combinations based on allelic status at S5. In addition, it can also precisely discriminate indica from japonica at this locus. Lanes 1–6: IR36, TKM6, IR64, ADT37, Jaya, W1263; lanes 7–12: Nipponbare, Akihikari, Koshihikari, Sasanishiki, Taipei 309, J84; lanes 13–18: Dular, Nagina22, Akshaydhan, Varadhan, RP2068, Anjali.

20% yield increase have been obtained (Sudhakar et al 2012) and these restorers are being used to develop new hybrids.

A specific breeding program was launched to develop usable TGMS lines by transferring the available TGMS gene(s) to well-adapted, high-yielding varieties. The newly developed TGMS lines were characterized for critical sterility point (CSP) and critical fertility point (CFP) to work out appropriate periods for their multiplication and hybrid seed production (Table 8).

Development of parental lines and hybrids suited to aerobic conditions

It is essential to develop hybrids for water-limited areas (aerobic) keeping in view the dwindling freshwater resources in the coming years. No hybrids have been released so far, especially for aerobic conditions, although hybrids are known to perform better under various abiotic stress conditions.

All the diverse parental lines were evaluated under aerobic conditions to identify promising entries. The highest frequency of promising entries was recorded in hybrids (45%), followed by IR64 introgression lines (17%), Teqing introgression lines (16%), and restorers (14%). The promising parental lines identified are being used to develop hybrids suited to aerobic conditions (Table 9).

Introgression of biotic stress resistance genes into hybrid rice parental lines

Biotic stresses such as bacterial blight (BB), blast, stem borer, leaffolder, and brown planthopper (BPH) affect the rice crop, including hybrids. Therefore, concerted efforts are needed to develop parental lines with resistance genes. With the advent of molecular breeding and the availability of markers tagged to most biotic stresses, it has become easy to incorporate resistance genes into parental lines so that the resulting hybrids can withstand the pressure of biotic stresses.

Table 8. Morphological characterization of newly developed TGMS lines.

TGMS line	Plant height (cm)	Days to flowering	No. of effective tillers	Panicle exsertion (%)	No. of spikelets	Anthesis time	Anthesis duration (min)	Panicle length (cm)	Critical temperature (°C)	
									Sterility	Fertility
DRR2S	77	94	14.8	81.2	165	1010-1215	125	19.9	31	23
DRR3S	77	92	16.0	82.3	139	0925-1220	175	22.7	29	24
DRR4S	86	94	14.4	79.0	199	0925-1225	180	24.5	30	23
DRR5S	55	106	16.8	70.2	158	0936-1215	159	24.0	31	23
DRR6S	72	98	10.6	85.7	165	0922-1310	238	24.0	32	24
DRR7S	76	91	10.4	79.7	140	0935-1215	158	23.2	29	26
DRR1S (check)	47	77	16.0	71.3	63	0920-1215	175	17.7	29	24

Table 9. Mean yield of entries tested in aerobic conditions.

Type of material	No. of entries	Five-plant yield (g)		Promising entries	
		Mean	Range	No.	%
IR64 introgression lines	140	103	60–130	24	17
Teqing introgression lines	135	106	58–129	21	16
I × J derivatives	250	92	35–115	25	10
Varieties	65	95	49–118	9	14
Hybrids	20	105	85–135	9	45
B lines	30	71	40–94	1	3
R lines	60	90	50–108	6	10
Total	700	99	35–135	95	14

The parental lines of Pusa RH10 (the first aromatic rice hybrid), Pusa 6B, and PRR78 are fortified with BB- and blast-resistance genes (Basavaraj et al 2010, Vikas et al 2012). Similarly, the parental lines of KRH 2 (the most popular and widely adopted hybrid), IR58025B, and KMR 3 are fortified with BB- and blast-resistance genes (Yadla Hari et al 2011). Many newly developed parental lines are being fortified with resistance genes for major diseases such as BB and blast and insect pests such as BPH.

The development of rice hybrids

As a result of concerted efforts over the last two decades, 59 hybrids have been released for commercial cultivation in different rice-growing states of the country and all the hybrids are based on the three-line breeding system. Among these, 31 have been released from the public sector, while the remaining 28 have been developed and released by the private sector. Central releases were 35 and state releases numbered 24.

The recently released hybrids show standard heterosis of 26–34% (Table 10), reflecting satisfactory progress being made in the development of new parental lines.

Careful analysis of the grain quality characters of the released hybrids clearly indicates significant improvement in grain quality traits such as head rice recovery (>60–65%), alkali spreading value (4–5), and intermediate amylose content (22–24%) of most of the new-generation hybrids released after 2006. More than 50% of the released hybrids possess long slender and long bold grains, thus limiting the spread of hybrid rice cultivation in southern Indian states where the preference is for fine-grain medium slender rice. With the development and release of hybrids with medium slender grain such as DRRH-3 from DRR, Hyderabad; TNAU Rice Hybrid Co4; 27P11 from Pioneer Overseas Corporation, Hyderabad; and JKRH 3333 from J.K. Agri Genetics Company, Hyderabad, the area under hybrid rice in southern Indian states is likely to increase in the coming years.

Table 10. Extent of standard heterosis observed in some recently released hybrids.

Name of hybrid	AICRIP years of testing	Yield (kg/ha)		Yield advantage over check (%)
		Hybrid	Inbred check	
DRRH-3	2005-07	6,074	4,620	31
27P11	2006-08	7,225	5,613	29
Indam 200-017	2007-09	5,384	4,121	31
VNR 202	2008-10	5,956	4,742	26
VNR 204	2008-10	7,023	5,226	34

Source: The respective hybrid release proposals.

Hybrids in the long-duration group hitherto unavailable are now being developed, the first in the series being CRHR 32 from CRRI, Cuttack. A few more hybrids are in the pipeline. With the availability of long-duration hybrids, hybrid rice area in the coastal regions and boro growing system is likely to increase.

Major challenges

Despite the very good progress made in hybrid rice breeding in the country, many issues still need to be resolved:

- Marginal heterosis. In highly productive rice-growing states, the yield advantage of hybrids over high-yielding inbred varieties is 10–15% only, which is not economically attractive to the farming community.
- Narrow genetic base. All the 59 released hybrids are based on a single cytoplasmic source (wild abortive), which may be prone to an outbreak of any major biotic stress.
- Diversified consumer preferences. Grain quality preferences are highly region-specific in India and developing hybrids to satisfy the quality requirements of diverse regions is a daunting task.
- Very few hybrids with late duration and limited choice of hybrids for unfavorable environments. Long-duration hybrids for coastal regions and boro systems and suitable hybrids for saline/alkaline soils are not available.
- Susceptibility of parental lines to major pests and diseases. The parental lines and hybrids are susceptible to major biotic stresses and minor diseases such as false smut, which is becoming a major threat to hybrid rice cultivation.
- Lack of molecular markers for the identification of maintainer-like *Rf* genes in the case of restorers. The identification of new maintainer lines has to be carried out in a conventional way and no molecular markers are available for their identification.

Current and future hybrid rice breeding programs in the country are being designed to tackle all the above mentioned issues in a concerted manner so that hybrid rice cultivation will expand and help increase production and productivity in the country.

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Identification of candidate genes for fertility restoration of wild-abortive cytoplasmic male sterile lines through mapping and sequencing

C.N. Neeraja, P. Balaji Suresh, and B.C. Viraktamath

For hybrid rice production, the wild-abortive (WA) system is the major cytoplasmic male sterility (CMS) source in indica rice. The fertility restoration of WA-CMS is reported to be controlled by two major loci, *Rf3* on chromosome 1 and *Rf4* on chromosome 10; however, the candidate genes involved in fertility restoration are yet to be identified. With an objective of identifying candidate *Rf* genes, *Rf3* and *Rf4* loci were fine-mapped and the putative candidate genes were identified and sequenced. Two mapping populations of approximately 1,500 F_2 progeny from KRH2 (IR58025A/KMR3R) and DRRH2 (IR68897A/DR714-1-2R) hybrids were analyzed using a set of RM (rice microsatellite) and designed microsatellite markers. Out of 85 markers for the *Rf3* locus and 131 markers for the *Rf4* locus, two linkage groups were constructed with seven polymorphic markers. The marker-delimited region as derived from linkage maps for *Rf3* was 4.9 to 5.1 Mb and for *Rf4* it was 18.1 to 18.8 Mb. In silico analyses have shown a total of 185 and 180 genes with approx. 10 major families and approx. 70 unique genes in both loci. Sequencing of candidate genes with TPR (tetra-trico peptide repeat)-like domain-containing proteins in the *Rf4* region and candidate genes associated with mitochondrial peptidases, pollen-specific proteins, and TPR-like domain-containing proteins indicated the involvement of TPR candidate genes in fertility restoration of WA-CMS in the *Rf4* locus and mitochondrial peptidase and pollen-specific proteins in the *Rf3* locus. Validation of the identified candidate genes for fertility restoration in the mapping populations and known set of restorers is in progress.

Hybrid rice technology is one of the proven technologies for enhancing productivity in several rice-based countries across the world. To develop rice hybrids, the three-line system consisting of a cytoplasmic male sterile (CMS) line (A), a maintainer line (B), and a restorer line (R) is mostly adopted. Though 20 independent CMS cytoplasms have been reported in rice, only three CMS system—wild abortive (WA), boro tai (BT), and Honglian (HL)—are mostly deployed for commercial hybrid seed production (Li and Yuan 2000, Fujii and Toriyama 2009). Of these, the WA system is widely used as a CMS source for indica rice. Genetic studies of fertility restoration in the WA-CMS system showed that the control of the trait is monogenic (Shen et al 1996);

digenic (Bharaj et al 1991); digenic with different types of interactions (Govinda Raj and Virmani 1988, Sohu and Phul 1995, Sharma et al 2001, Waghmode and Mehta 2011); trigenic (Kumar and Chakrabarti 1983, Sarkar et al 2002), and with trigenic interactions (Huang 1987, Hossain et al 2010).

Using a molecular mapping strategy, chromosomal locations of the *Rf* genes for various CMS systems in rice have been identified. For the *Rf1* locus restoring BT-CMS, two pentatricopeptide (PPR) genes have been identified (Wang et al 2006). Another fertility locus *Rf2* in lead rice (LD-CMS) in japonica has been fine-mapped on chromosome 2 (Shinjyo and Sato 1994, Fujii and Toriyama 2009). Two loci, *Rf5*(t) and *Rf6*(t), were identified for HL-CMS on chromosome 10 (Huang et al 2000, Liu et al 2004).

For WA-CMS, two loci on chromosomes 1 and 10 have been consistently mapped (Zhang et al 1997, Yao et al 1997, Tan et al 1998, Jing et al 2001, He et al 2002, Zhang et al 2002, Mishra et al 2003, Singh et al 2005, Ahmadikhah and Karlov 2006, Ahmadikhah et al 2007, Bazarkar et al 2008, Sattari et al 2008, Sheeba et al 2009, Ahmadikhah and Alavi 2009, Nematzadeh and Kiani 2010, Ngangkham et al 2010). Ngangkham et al (2010) fine-mapped the *Rf4* locus in Basmati restorer line PRR78 within an interval of 0.8 cM and developed a candidate gene (CG)-based marker from the PPR3 gene based on sequence information derived from japonica Nipponbare. Attempts were made to use these two loci for marker-assisted selection (MAS) to identify restorer lines possessing *Rf* genes for WA-CMS to expedite phenotype-based screening (Nas et al 2003, Sattari et al 2007, Sheeba et al 2009, Ngangkham et al 2010). Therefore, our study was undertaken to identify candidate genes for *Rf3* and *Rf4* loci through sequencing and mapping.

Materials and methods

Two mapping populations of approximately 1,500 F_2 progeny derived from hybrids KRH2 (IR58025A/KMR3R) and DRRH2 (IR68897A/DR714-1-2R) were studied for the mapping of *Rf3* and *Rf4* loci, and the pollen fertility of parents and the mapping population was determined using 1% I-KI stain (Virmani et al 1997) and classified following the Standard Evaluation System (IRRI 1996). Total genomic DNA from fresh and young leaves of parents and segregating populations was isolated using a modified protocol of Zheng et al (1995). Based on the position reported for markers for *Rf3* and *Rf4* loci, several primers were designed for microsatellites and candidate genes using Primer 3.0 software. A polymorphism survey between parents and selective genotyping of polymorphic primers in two phenotypically distinct classes in segregating populations for pollen fertility was performed (Nandi et al 1997). Genetic maps were constructed using MapDisto v. 1.7 software (Lorieux 2007) and QTLs were identified using QTL Cartographer 2.5 (Wang et al 2010). QTL interactions in mapping populations were analyzed using QTLNetwork 2.1 software (Yang et al 2008). Sequences of the polymorphic products were compared between the A and R lines and also with the sequences of japonica subspecies (Nipponbare) using the CLUSTALW multiple sequence alignment tool employing BIOEDIT software.

Results and discussion

Elucidation of the mechanism of WA-CMS and its fertility restoration is critical for enhancing breeding efficiency by developing a marker system for the identification of restorers, identifying superior alleles for fertility restoration, and pyramiding and introgressing *Rf* genes. In our study, both mapping populations showed continuous variation in pollen fertility, ranging from 0 to 100%, suggesting the involvement of a QTL in fertility restoration of WA-CMS. Using selective genotyping, polymorphic markers have been screened in both mapping populations for the construction of linkage groups for the *Rf3* and *Rf4* loci. Out of 85 markers for the *Rf3* locus and 131 markers for the *Rf4* locus, two linkage groups were constructed with seven polymorphic markers. For the *Rf3* locus, the genetic map distances ranged from 10.4 cM (KRH2) to 11.7 cM (DRRH2). For the *Rf4* locus, the genetic maps spanned from 11.4 cM (DRRH2) to 14.1 cM (KRH2). In both populations, a QTL (qWARF-1-1) with a high LOD threshold was detected in the *Rf3* locus using QTL Cartographer. For the *Rf4* region, two QTLs were mapped in both mapping populations. One QTL (qWARF-10-1) spanned two candidate gene markers and the other QTL (qWARF-10-2) encompassed the most reported marker, RM6100. The contribution and interaction of the identified QTLs in our study were analyzed using QTLNetwork software (Yang et al 2008). A QTL (qWARF-1-1) explaining 31% of the phenotypic variance in KRH2 and 23% of the phenotypic variance in DRRH2 was identified for the *Rf3* locus. In the *Rf4* region, a QTL (qWARF-10-1) was identified with two candidate gene markers explaining phenotypic variance of 41% in KRH2 and 43% in DRRH2. In both mapping populations, the interactions were identified between one QTL of *Rf3* (qWARF-1-1) and two QTLs of *Rf4* (qWARF-10-1 and qWARF-10-2) (Balaji Suresh et al 2012). From the analysis of two types of QTL identification software in two mapping populations, two loci together explained 65% to 75% of the phenotypic variance of the trait, suggesting their utility in developing a marker system. However, development of markers for a putative third locus or more QTLs with smaller effects is needed for a marker system achieving 100% efficiency.

The marker-delimited region as derived from linkage maps for *Rf3* was 4.9 to 5.1 Mb and for *Rf4* it was 18.1 to 18.8 Mb. *In silico* analyses showed a total of 185 and 180 genes with approx. 10 major families and approx. 70 unique genes in both loci. For the identification of candidate genes, only TPR genes and genes directly involved in pollen biosynthesis were considered as putative candidate genes; however, the identification of genes other than TPR genes involved in fertility restoration of Chinese wild (*CW*) type of CMS (Fujii and Toriyama 2009) and lead rice type of CMS (Itabashi et al 2011) necessitates inclusion of a wide range of candidate genes. The use of a sequence of candidate genes in the *Rf4* region from an IR24 indica BAC clone (AB110443), which is reported to be a strong restorer for WA-CMS with two dominant genes (Gao 1981), has resulted in two polymorphic CG-based primers (PPR683 and PPR762). Sequence analysis of PCR products of DRCG-RF4-8 targeting PPR683 showed a 6-bp deletion in A lines and a 327-bp deletion in R lines in comparison with the sequence of an IR24 BAC clone (AB110443). Association of the deletion in this gene with fertility restoration of WA-CMS is being reported for the first time. Sequence analysis of PCR products targeting PPR762 and a comparison of sequences identified a deletion of 106 bp in R lines. A similar deletion in the same gene was also reported by Ngangkham et al (2010). Sequence analysis of *Rf1a* and *Rf1b* fertility restorer genes of BT cytoplasm showed that substitutions are responsible for the functional variation (Wang et al 2006); hence, the functional significance of these deletions at the PPR genes of the *Rf4* locus needs to be deciphered.

In our study, *Rf3* and *Rf4* loci were fine-mapped and a few candidate genes were identified and sequenced. The identified structural polymorphisms were validated in the mapping populations to identify the candidate genes and experiments are in progress for finer mapping of these two loci along with the identification of other *Rf* genes controlling fertility restoration of WA-CMS.

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Notes

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The hybrid rice breeding program in the Philippines

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The start of hybrid rice technology in the Philippines in 1998 was inspired by the remarkable gains achieved by China. With the International Rice Research Institute (IRRI) as the impetus in this endeavor, the Philippine Rice Research Institute (PhilRice) intensified its hybrid breeding program using germplasm from IRRI and initially developed hybrids. Moreover, the Philippines' technical capacity in hybrid rice development and use was also built with collaboration with various Chinese Institutions. In 1994, the first IRRI-bred hybrid, PSB Rc26 or variety Magat, was piloted in the Philippines. In 1997, PSB Rc72H (Mestizo) was released, which became the first successfully launched variety for commercialization. From then on, hybrid technology became a national development strategy. Public institutions developed 18 hybrids from 2002 to 2011, and, with intensified public-private partnership, the participation of 12 private companies resulted in the approval of 24 hybrid varieties for commercial cultivation by the National Seed Industry Council.

Hybrid rice remains a strong and reliable technology in our quest for rice self-sufficiency and competitiveness. To be able to achieve current breeding goals, a focus on two main "product development" platforms was conceptualized: (1) Extensively characterize the elite germplasm pool, capitalizing on the progress of the inbred breeding program. The use of biotechnology and new breeding tools will boost the quality of prebreeding materials for the development of better high-yielding, pest-resistant, and excellent-quality hybrid rice varieties. (2) Develop further seed production research and a support system to increase seed yield and productivity at various sites with different climatic conditions. In this way, the performance of the hybrids in current and new potential areas will have customized specific seed production technologies for producing hybrid seeds readily available to farmers.

Keywords: hybrid rice, heterosis, cytoplasmic male sterility CMS), fertility restoration, rice self-sufficiency, seed production research

Breeding for new rice varieties in the Philippines is a continuing pursuit to cope with increasing and changing market demand, evolving insect pests and diseases, and shifting production constraints. Moreover, with the country's increasing population and decreasing area of prime rice lands, the need to dramatically increase production per unit area to cope with the demand for rice is inevitable. Equally crucial is the competing need for water for agriculture, industry, and domestic household uses. Therefore, superior genotypes that would maximize the use of scarce land and water resources should be sought. Under favorable transplanted areas, strategies to improve yield such as ideotype breeding, the use of diverse parentals, and the use of three-line or two-line hybrid rice systems were shown to work under Philippine conditions.

Heterosis breeding has become an alternative strategy for inbred rice development. The expected increment in grain yield from excellent hybrids is at least 15% per hectare over inbreds. Excellent hybrids also offer higher income opportunities to farmers through either F_1 cultivation or parental seed production.

Hybrid rice breeding at the Philippine Rice Research Institute (PhilRice) is one component of the program Developing Technologies to Surpass the Dry Season Irrigated Lowland Rice Yield Plateau (SYP). The project encompasses breeding and improvement of parental lines, seed production of parentals and experimental hybrids, and evaluation of experimental hybrids. In this chapter, we provide an update on the historical background, accomplishments, and current prospects and strategies of hybrid rice breeding at PhilRice from 1988 to date.

Historical background and significant achievements (1985-2010)

The hybrid rice development project in the Philippines through PhilRice was developed as a research strategy to achieve the goals and objectives of the Rice Varietal Improvement Program (RVIP). This undertaking was established in the 1990 wet season to duplicate the yield-increasing benefits of heterosis breeding achieved in China. The momentum to intensify the hybrid breeding program was fueled by the availability of and accessibility to IRRI's germplasm and initial efforts were made as early as 1978.

Since the creation of PhilRice in 1985, as it followed the path of increasing yield potential in rice, the past 25 years for hybrid rice breeding can be described in four phases. The **first phase (1985 to 1997)** marked the pioneering years in introducing important germplasm from IRRI and partnership with the leading Chinese rice R&D institutions, starting with Yunnan Agricultural University (YAU). At this time, the common tools for breeding were cytoplasmic male sterility (CMS) and fertility restoration systems for three-line hybrid development. During this phase, IRRI made available many CMS lines, maintainers, and restorer lines in the tropics, the most popular of which were IR58025A and IR62829A. In 1994, PSB Rc26H (or Magat), the first hybrid in the Philippines, was commercially released for cultivation in irrigated lowland.

In the **second phase (1998-2005)**, the Philippine government launched its hybrid rice program (in 1998). PSB Rc72H (or Mestizo hybrid) was released and has been fairly successful. More importantly, the country has gained experience in hybrid rice technology. Farmers became familiar with hybrid rice cultivation and competent seed growers produced and distributed high-quality hybrid seeds. It was in this phase that the government recognized hybrid rice as a national development strategy. In 2000, a bilateral agreement between China and the Philippines was forged, giving rise to the Philippine Sino Center for Agricultural Technology (PhilSCAT). Starting in 2003, PhilRice collaborated with PhilSCAT in the areas of hybrid rice technology and rice engineering and mechanization. This was strengthened by support from the Food and Agriculture Organization (FAO) with the granting of a Technical Cooperation on "Strengthening National Capacity for Hybrid Rice Development and Use" and the continuing formal and informal collaborative arrangements with 13 research entities, including universities and government agencies in China (2005). The country launched the Hybrid Rice Commercialization Project (HRCP) beginning in 2001 and became the cornerstone of the rice self-sufficiency program encompassing hybrid rice R&D, seed production, technology promotion, information dissemination, credit provision, marketing assistance, and seed industry development. By 2004, the area planted to hybrid rice in the country surpassed 208,000 ha, making the Philippines the country with the fourth-largest hybrid rice area in the world following China, Vietnam, and India. In 2005, hybrid rice further expanded to 360,000 ha.

In the **third phase (2006-10)**, the major R&D thrusts were ecosystem-based and output-driven. Hybrid breeding with more focused and client-sensitive activities was placed under the Favorable Environment Program. This phase also marked an increase in the participation of private companies for hybrid rice development and also generated many commercial hybrids for the irrigated lowland ecosystem: 11 from the public sector (IRRI, PhilRice, University of the Philippines Los Baños, and PhilSCAT) and 11 from the private sector (Bioseed, HyRice, Syngenta, Bayer, and Pioneer) (Table 1). A majority of the hybrids were three-line hybrids, except for Mestiso 19 and 20, which were the first two-line hybrids in the Philippines.

Current research strategies (2011-16)

A dynamic breeding program that will complement private seed company efforts has been the current driving force of the team. This is to make available public-bred hybrids with comparable or better performance than those released by private seed companies. As a startup mechanism, some specific guiding principles were incorporated in the hybrid rice breeding program as follows:

1. The link between inbred and hybrid rice breeding work was intensified to hasten the progress of the hybrid rice breeding project. Selected early-generation or outstanding lines from inbred rice breeding increased the number of early-generation and high-yielding hybrids testcrossed to elite inbred parental lines. Moreover, B and R line improvement work was also possible for inbred varieties or donor germplasm for further breeding.
2. Collaboration and teamwork within and among the hybrid rice breeding teams of PhilRice Central Experiment Station and two other branch stations in Isabela and Laguna are gaining ground. Cross visits of researchers were organized to evaluate new hybrid combinations as well as converted parentals and hybrids of existing hybrid varieties in the bacterial leaf blight (*Xa* genes) background as well as in seed purification activities.

Table 1. List of Philippine hybrid rice varieties commercially released from 2006 to 2010.

Variety	Line designation	Year approved	Breeding institution
NSIC Rc136H (MESTISO 7)	IR78386H	2006	IRRI
NSIC Rc162H (MESTISO 8)	BIO 401	2007	BIOSEED
NSIC Rc164H (MESTISO 9)	RIZALINA 28	2007	HYRICE
NSIC Rc166H (MESTISO 10)	PSD 3	2007	SYNGENTA
NSIC Rc168H (MESTISO 11)	BCS 064	2007	BAYER
NSIC Rc174H (MESTISO 12)	LP 0331	2008	PHILSCAT
NSIC Rc176H (MESTISO 13)	LP 0353	2008	PHILSCAT
NSIC Rc178H (MESTISO 14)	LP 0330	2008	PHILSCAT
NSIC Rc180H (MESTISO 15)	BCHR 4172	2008	BIOSEED
NSIC Rc196H (MESTISO 16)	PR31191H	2009	PHILRICE
NSIC Rc198H (MESTISO 17)	PR31204H	2009	PHILRICE
NSIC Rc200H (MESTISO 18)	BCS 065	2009	BAYER
NSIC Rc202H (MESTISO 19)	PRUP 7	2009	PHILRICE & UPLB
NSIC Rc204H (MESTISO 20)	PRUP 9	2009	PHILRICE & UPLB
NSIC Rc206H (MESTISO 21)	IR83199H	2009	IRRI
NSIC Rc208H (MESTISO 22)	NK 6401	2009	SYNGENTA
NSIC Rc210H (MESTISO 23)	PHB 71	2009	PIONEER
NSIC 2010 Rc228H (MESTISO 24)	HR4842H	2010	HYRICE
NSIC 2010 Rc230H (MESTISO 25)	IR82363H	2010	IRRI
NSIC 2010 Rc232H (MESTISO 26)	IR82372H	2010	IRRI
NSIC 2010 Rc234H (MESTISO 27)	NK 5017	2010	SYNGENTA
NSIC 2010 Rc236H (MESTISO 28)	SW 836	2010	SEEDWORKS

3. Integration of biotechnology work with inbred and hybrid rice breeding is in place to better monitor the true-to-typeness of the materials generated. Thus, breeders may be able to confirm or safeguard against drift away from the original parents sought for conversion. It is not often sufficient to just check for the presence or absence of the marked genes; there must be safeguards that the genes are in the right background(s).
4. Management of systematic record-keeping and sharing of information is an important component of breeding management and this helps provide strategies for reliable and secure accessibility to information.
5. The acquisition of breeding materials and new germplasm from various sources remains a top priority for all breeding projects to provide greater diversity to the upcoming materials in the program.
6. Capacity enhancement of team members through formal and on-the-job training programs has been a regular part of the program. This includes not only the breeding process but also the production of nucleus and breeder seeds of hybrid and parental lines as well as their appropriate cultivation technologies.

In the implementation of **Phase 4 (2011-16) of the program**, the level of agronomic performance of the 14 hybrid varieties released in 2011 was assessed. These status profiles can be used as a baseline for target yield, resistance, and grain quality parameters to bring about genetic gains in breeding.

Yield is the primary consideration in breeding new hybrids. Hybrids are released based on their 15% or higher yield advantage over the best inbred variety as a check. The performance of new accredited varieties in 2011 was determined by showing the average and maximum yields attained by each variety while they were being evaluated in National Cooperative Tests (Fig. 1). Results showed that the average yield of the 14 hybrids was 6.1 to 7.2 t/ha while the maximum yield attained was 8.9 to 11.4 t/ha. Generally, the public-sector hybrids were observed to have higher yielding ability.

In terms of resistance to major diseases, a majority of the hybrids were relatively intermediate to blast and susceptible to bacterial leaf blight and tungro virus disease (Fig. 2).

For milling quality, a majority of the hybrids passed the standards for brown rice, milling, and head rice recovery (Fig. 3). Apparently, however, the hybrids were inferior in premium milling and head rice potential. The preference of Filipinos for intermediate amylose content has been incorporated in both inbred and hybrid varieties. More than 70% of the hybrids were in the range of 20.1% to 25% amylose content (Fig. 4). For physical attributes, breeding has been skewed toward long and slender grain size and shape, grain length from 6.6 to 7.4 mm, and length/width ratio from 2.0 to 3.0 for grain shape. However, for the chalky character, a majority of the hybrids had more than 15.0% chalkiness, which is beyond the standards (Fig. 5).

Opportunities and prospects

Based on the guiding principles and breeding performance, an industry-inspired framework of the hybrid rice breeding program for 2011-16 has been laid down to support the national goal of attaining and sustaining rice self-sufficiency (Fig. 6).

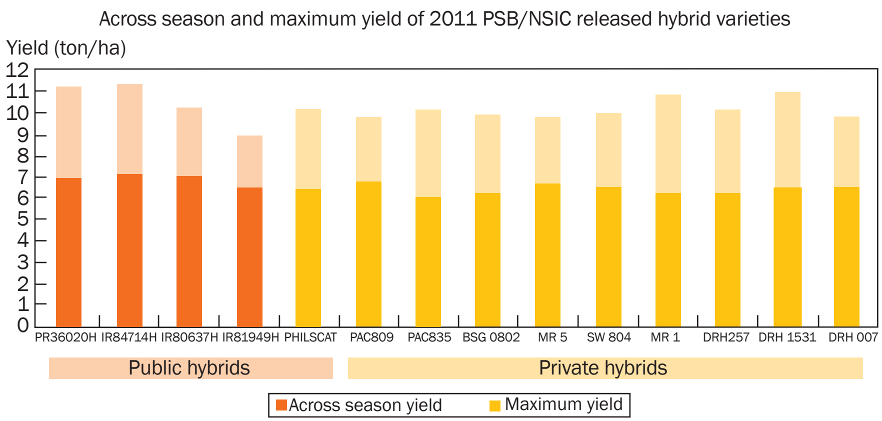

Fig. 1. Yield profile (across seasons and maximum) of public- and private-sector hybrid varieties in 2011 in National Cooperative Tests.

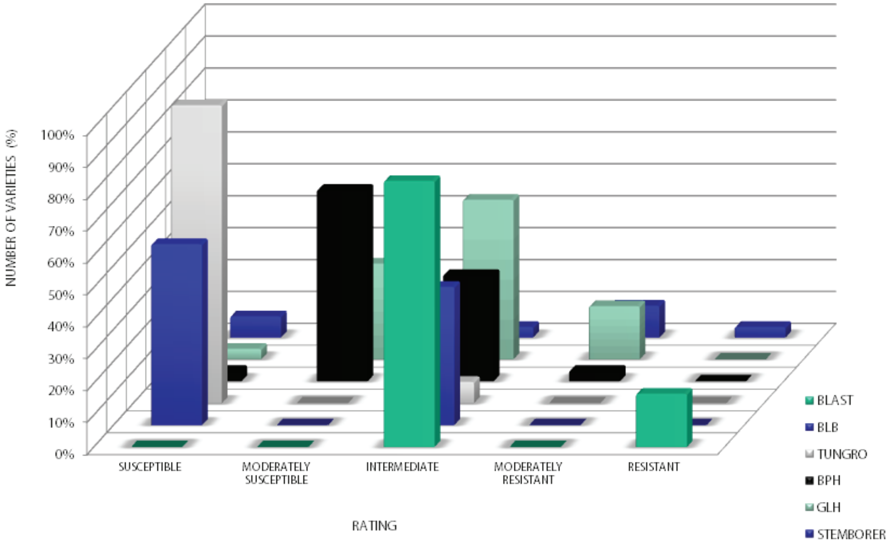

Fig. 2. Reaction pattern of the 2011 hybrid rice varieties to major diseases.

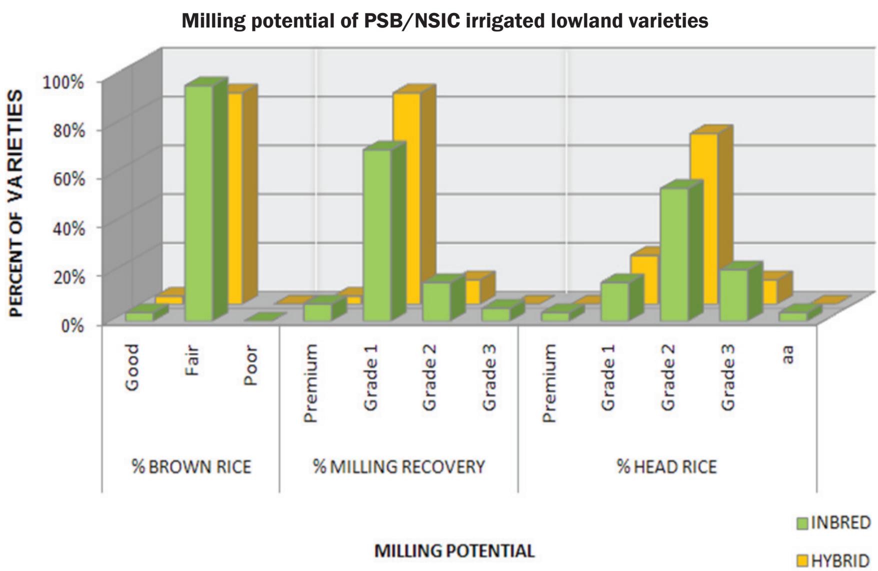

Fig. 3. Milling quality profile of inbred and hybrid varieties released from 1994 to 2011.

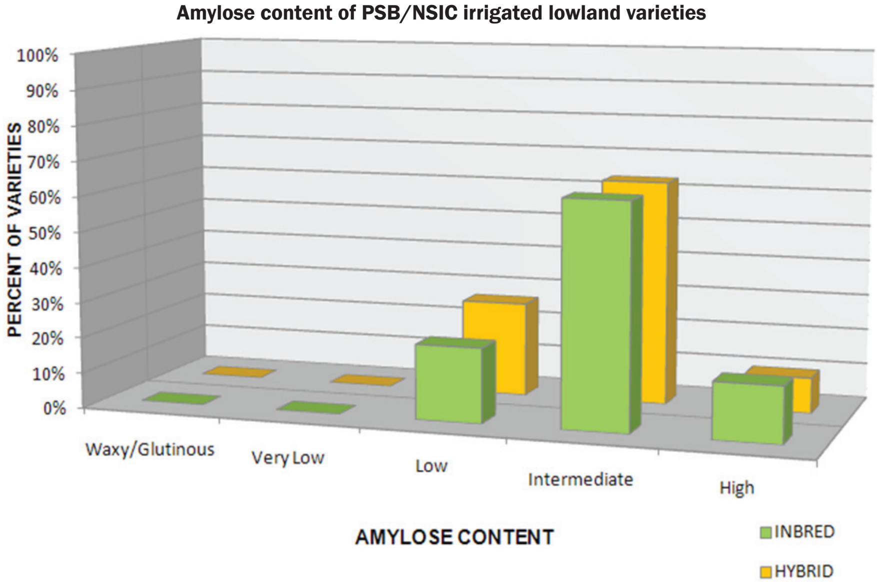

Fig. 4. Amylose content profile of inbred and hybrid varieties for irrigated lowland approved from 1994 to 2011.

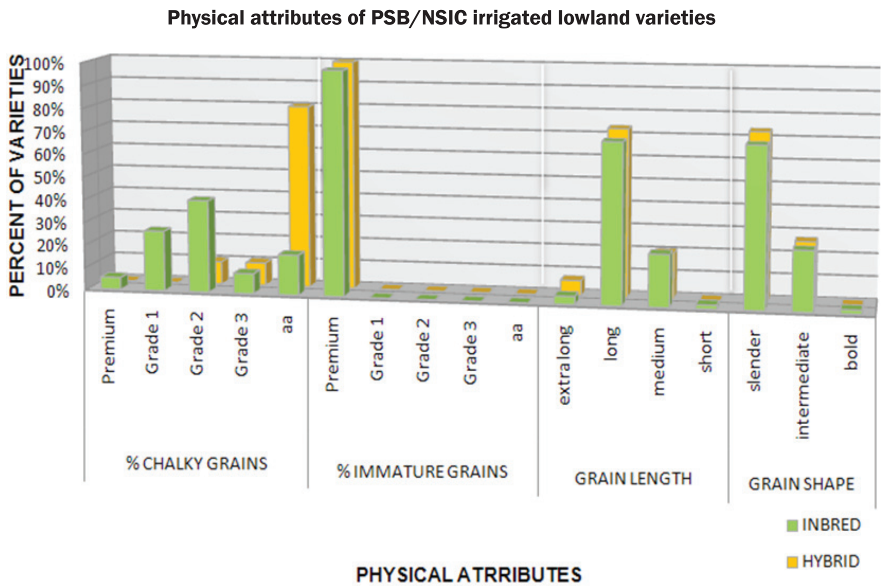

Fig. 5. Physical attributes of the inbred and hybrid varieties for irrigated lowland approved from 1994 to 2011.

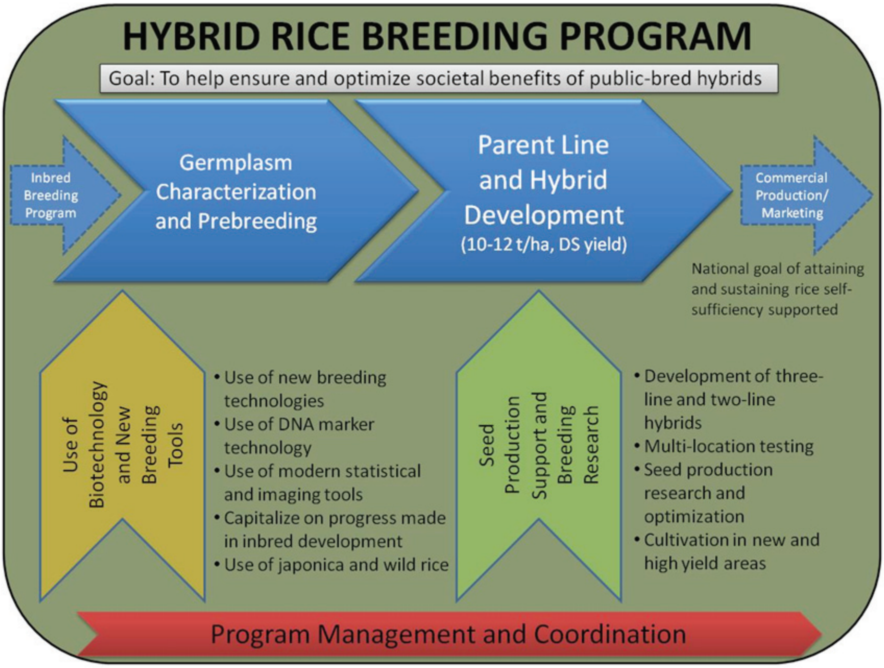

Fig. 6. Framework of PhilRice's hybrid rice breeding program (2011-16).

To be able to achieve the breeding goals, two main "product development" strategies have begun. One is to extensively characterize the elite germplasm pool and capitalize on the progress made in the inbred breeding program as to their suitability as parental lines and as a source of important traits to widen the gemplasm base through prebreeding. Examples are the introgression of yield-enhancing traits from japonica and wild rice. This strategy is being supported by the use of DNA marker technology and new breeding tools. Second is to develop the seed production research and support system to increase seed yield and productivity, especially in hybrid seed production. In addition, expansion of hybrid cultivation to new areas such as the favorable rainfed ecosystem is also a target.

Breeding priorities

1. With yield as the principal consideration in developing high-yielding and stable hybrids, improvement of plant architecture is prioritized. Plants with aq strong culm and thick and erect leaves are of importance and this will aid in breeding for varieties that could support high grain yield (target of 12 t/ha). Improving hybrid parental lines in terms of productivity in seed production is being emphasized. For diseases, bacterial leaf blight resistance will be incorporated as this is the most predominant disease in the current hybrid varieties released in the Philippines.

2. For grain quality characteristics, the focus will be primarily on chalkiness, which has a great impact on the pricing of paddy rice produced by farmers. Millers have been downgrading the price of paddy rice of hybrid rice varieties because of chalkiness. Increasing the target for milling recovery from 62−65% to about 70% and head rice potential from 48% to higher is also beneficial for market preference while maintaining intermediate amylose content.
3. Other characteristics that may be important traits for the future are also considered such as tolerance of abiotic stresses and the development of nutrient-dense hybrid varieties.
4. Testing in more test locations increases the chances of coming up with excellent hybrids. Testing in high-yield environments using GIS data is also critical to determine the yield potential of these hybrids.
5. Another target is to expand seed production research to develop high seed yield protocols at various sites with different climatic conditions. This is basically matching specific seed production technologies with potential areas for producing hybrid seeds.
6. A final target is to embark on public-private partnership to fast-track the commercialization of publicly released hybrid varieties through innovative modalities such as joint ventures, nonexclusive licensing, etc.

Conclusions

Hybrid rice remains a strong and reliable technology jn our quest for rice self-sufficiency and competitiveness. Rice farmers in the Philippines and elsewhere will benefit from accelerated access to hybrid rice–based technologies, such as more and better hybrids, quality seed, and knowledge and services provided by both the private and public sector.

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Screening of hybrids and parental lines for association of physiological traits to identify heat-tolerant and nitrogen-use-efficient rice genotypes

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Identifying heat-tolerant rice genotypes with enhanced nitrogen-use efficiency is one of the important areas of research for sustainable rice production in the changing climate scenario. A comparison of various physiological traits contributing to N-use efficiency and heat tolerance in the parents involved in developing hybrids for their heterosis will provide insights to hasten hybrid development to further sustain rice production in the coming years. Forty restorer lines, two A lines, four B lines, and three released hybrids were grown in fields for two consecutive seasons under treatments with N at 100 kg/ha (N 100) and native N (N 0) and were assessed. The results indicated that responses to nitrogen among the parental lines and hybrids varied widely for the 18 characters—morphological (plant height, tiller number, and effective booting tillers), physiological characters (leaf thickness, temperature, rolling times, leaf area, chlorophyll, N content in straw and grain), and yield attributes (straw, total dry matter, panicle number and weight, filled and unfilled grain weight, grain yield, and harvest index)—that were assessed. The existence of variability in leaf thickness did not correlate with chlorophyll at N 0 and N 100. Hybrids and parents exhibited higher % leaf rolling times with a lower reduction in leaf area. Stomatal number and aperture supported these observations. Also, hybrids had lower leaf temperature, perhaps contributing to the superior water retention characteristics. Overall N content in straw was higher; while it did not differ much in grain though individual genotypic differences existed in the parents and hybrids.

Rice (*Oryza sativa* L.), wheat, and maize are important food crops of the world, supplying most of the calories consumed by the global population. China, India, Indonesia, Bangladesh, and Vietnam are the top rice-producing and -consuming countries in the world (FAOSTAT 2010). The world population is rising exponentially, leading to increased demand for rice consumption. In the current scenario, variation in climate change is one of the major constraints to rice production. The Intergovernmental Panel on Climate Change (IPCC) reported that the world temperature is increasing every year. The average increase in air temperature was 0.5 °C in the 20th century and the temperature is projected to further increase by 1.5 to 4.5 °C. (IPCC 1995, Peng et al 1999). Higher temperature can alter plant water-use efficiency (Mazorra et al 2002, Wahid et al 2007). High temperature also reduces nutrient-use efficiency, particularly nitrogen, a macronutrient, which affects crop yields (Tirol-Padre et al 1996, Imai et al 2008). It is an important structural component, especially of chlorophyll, which is directly involved in harvesting solar energy and producing dry matter (Dalling 1985, Samonte et al 2006). During the Green Revolution, rice yield improvement was achieved with the cultivation of N-responsive dwarf varieties (Sheehy et al 2008). From then onward, the usage of fertilizer in rice production has increased, leading to increased demand for fertilizer production and increased production cost of rice. However, all cultivars do not respond to fertilizer and concentrating nitrogen in rice plants does not raise grain yield every time (Samonte et al 2006), and at times excessive fertilizer application results in adverse environmental effects due to volatilization and leaching into soil, thereby causing groundwater pollution (Bohlool et al 1992, Samonte et al 2006).

High temperature and nitrogen limitation thus led to negative impacts on rice yields. Fortunately, the existence of a broad genetic base in rice and its readiness to adopt features by means of a morphological and physiological nature in germplasm should provide an avenue to counteract the challenges of climate change. In this context, hybrids provide an opportunity to combat the various stressful environments to which crops are subjected. Thus, high temperature and nitrogen interaction could play pivotal roles in determining rice yields in a climate change scenario. Hybrids might be an alternative yield-increasing strategy of rice as a rise in yield potential was made possible by indica hybrids (Peng et al 1999, Fageria 2007). In view of this, screening of parental lines and hybrids under limited N and in an N-rich environment was investigated for features of physiological adaptability.

Materials and methods

During 2010-11, field experiments with 40 restorers, 2 A lines, 4 B lines, and 3 hybrids, were grown under normal agronomic practices with treatments of N applied at 100 kg/ha and native N.

Observations

In situ leaf chlorophyll content (Minolta Corporation's Chlorophyll SPAD-502 plus, USA), leaf thickness (Model 06-664-16, Fisher Scientific, USA), digital Vernier Calipers, and leaf temperature using an IR thermometer (Fischer Scientific, USA) were measured. Leaf rolling was determined *in vitro* between 1100 and 1230 as described in the DRR annual report (2007-08). Nitrogen content from straw and grain was estimated according to the Kjeldahl method of N estimation (1883). All these parameters were determined twice in the cropping season and data were pooled for analysis.

Stomata

Leaf stomatal impressions obtained from both the upper and lower epidermis peelings as observed with a Nikon light microscope under 40X resolution (Nikon Model ALPHA PHOT-2 YS2-H, China) and stomatal number, width, and length were measured using a micrometer scale. For each group of parental lines and hybrids based on population size, two to five cultures were tested and their mean calculated.

At the physiological maturity stage, morphological characters such as plant height, tiller number, and effective booting tillers were recorded. Yield and yield components were recorded from five hills. Data from the two seasons were pooled and analyzed using Statistix 8.1 (Analytical Software Inc., USA).

Results

The results of the experiment were described in two sections: (1) N response irrespective of parental lines and hybrids and (2) response of genotypes group-wise irrespective of N.

N response irrespective of parental lines and hybrids

Genotypic responses to the application of nitrogen irrespective of parental lines and hybrids for morphological, physiological, and yield components are presented in Figures 1–3. It is obvious that, in a nitrogen-limited environment, the plants would be shorter (75 cm) with few tillers (7) and also variation was 38% in effective booting tillers. The reduction in leaf area before and after leaf rolling is 17 and 7 cm^2, respectively, under N 0. Physiological parameters such as leaf thickness did not vary (0.14 mm) between the treatments, whereas leaf rolling time response improved (26%) due to N treatment (Fig. 2). On the other hand, leaf area increased before and after rolling (24 and 8–9 cm^2), with a slight improvement in chlorophyll content and almost 2 °C lower leaf temperatures observed under N 100 vis-à-vis N 0. The application of N resulted in improved yield and its components to varying degrees. On average, only two panicles developed due to N application, which is marginal, but, for panicle weight, filled

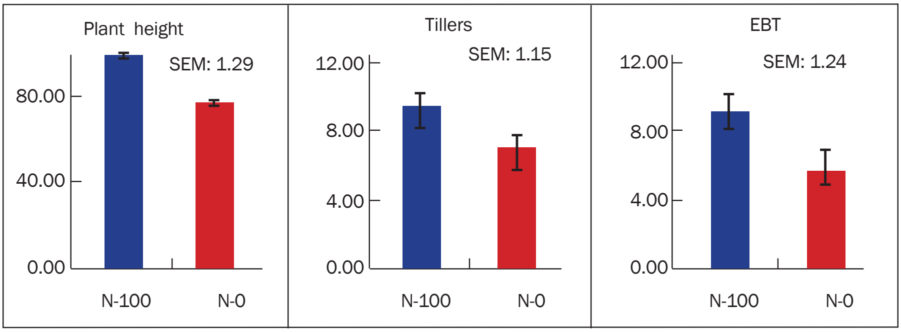

Fig. 1. Morphological changes (mean values) as influenced by N application irrespective of parental lines and hybrids.

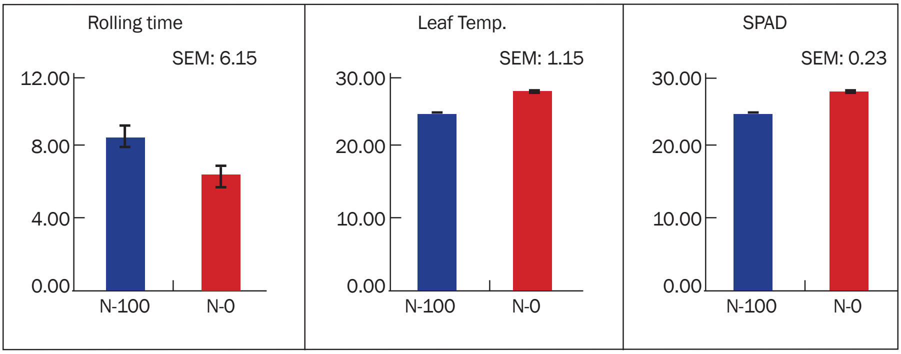

Fig. 2. Physiological changes (mean values) as influenced by N application irrespective of parental lines and hybrids.

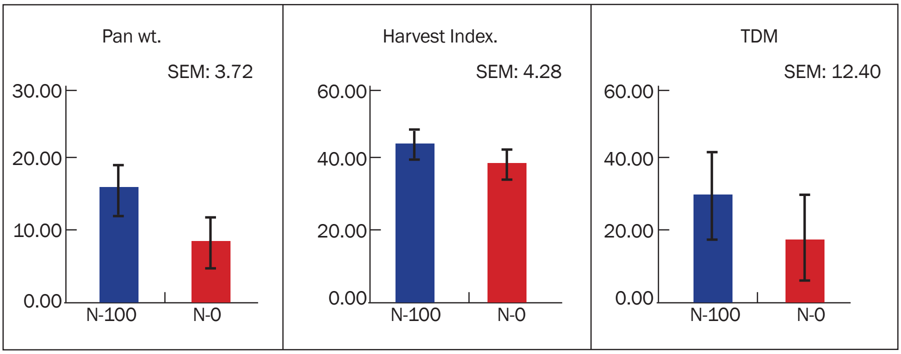

Fig. 3. Panicle weight (g), harvest index (%), and total dry matter (g) as influenced by N application in parental lines and hybrids.

grain weight, and total grain weight, an almost 50% increase was noticed. A concurrent increase in straw (32%) and total dry matter weight (42%) further corroborated that N application resulted in both growth and development (Fig. 3). With reference to % N content, a difference was observed only in straw (0.47% and 0.41% under N 100 and N 0, respectively), whereas, in grain, % N content (1.32%) did not increase significantly between treatments. However, at the individual level, genotypes differed significantly with reference to % N content in both straw and grain in these lines.

Response of genotypes group-wise

Group-wise mean values and enhancement in crop growth attributes and physiological responses as a result of nitrogen application (as % change) are presented in Tables 1–3. N application promoted a 20.3% increase in mean plant height. Among the different lines, R lines (23%), A lines (22%), and B lines (24%) had a similar influence, while, in hybrids, it was 12% only. An average of 38% change in tiller number and 47% in effective booting tillers was observed due to N application. Both B lines and hybrids were similar in their response while restorers responded poorly for this trait.

Table 1. Growth changes (%) in relation to N application in parental lines and hybrids.

	Restorers	A lines	B lines	Hybrids	Average
Plant height	23.2	22.0	24.0	12.0	20.3
Tiller no.	17.4	23.6	54.9	55.2	37.8
Early-bearing tillers	33.3	43.1	56.5	53.9	46.7

Table 2. Percent changes in physiological attributes in parental lines and hybrids during crop growth period.

	Restorers	A lines	B lines	Hybrids	Average
Rolling time	29.9	0.7	8.0	18.6	14.3
Normal leaf area	28.3	36.5	43.1	21.2	32.3
Rolled leaf area	19.0	24.9	36.0	26.2	26.5
SPAD reading	9.6	1.3	−1.1	11.9	5.4
Leaf temp.	−11.5	−10.4	−13.6	−17.7	−13.3

Table 3. Yield and its components (%) as influenced by N application in parental lines and hybrids.

	Restorers	A lines	B lines	Hybrids	Average
Panicle wt.	50.3	28.2	58.7	43.8	45.2
Total no, of panicles	29	28	47	23	31.4
Fresh grain wt.	49.7	14.6	62.1	40.4	41.7
Total grain wt.	48.6	21.2	61.8	42.0	43.4
Unfilled grain wt.	37.8	72.2	60.1	56.1	56.6
Straw wt.	32.8	30.9	31.3	38.0	33.2
Total dry matter	42.2	29.4	45.7	41.3	39.7
Harvest index	13.3	−12.2	21.5	2.6	6.3

The highest plant height was recorded in hybrids, with an average of 93.78 cm. Also, in leaf rolling time response due to N application, R lines and hybrids showed superiority (30% and 18%, respectively) compared with A and B lines (0.6% and 8%). Leaf temperature dropped by −17.7% in hybrids, whereas A lines were poor in their response to a reduction in temperature (−10.4%). N application resulted in an increase in leaf surface area by 43.1% in B lines, by 36.5% in A lines, by 28.3% in R lines, and by 21.2% in hybrids. Leaf area declined markedly because of leaf rolling in A, B, and R lines under stress while the reduction in leaf area was lower in hybrids. Leaf thickness did not vary with the application of N in these genotypes though individually hybrids were superior (0.15 mm).

Stomatal distribution on the adaxial side was higher in A lines, with a mean of 18.0, followed by R lines, B lines, and hybrids, whereas, on the abaxial surface, B lines had more stomata, with a mean of 22. R lines had greater stomatal length and width, followed by hybrids, A lines, and B lines (Fig. 4).

Panicle weight was found to be higher in hybrids, with a mean of 15.37 g/hill, followed by restorers. Similar observations were made for filled grain weight, whereas there was not much variation in the number of panicles among parental lines and hybrids.

Yield and yield components varied widely in response to N application. For instance, the increase in panicle weight was as high as 58.7% (in B lines) and as low as 28.3% (in A lines). Panicle number was around 26% in restorers, A lines, and hybrids. All these morpho-physiological responses led to an improvement in the harvest index in hybrids (2.6%), restorers (13.3%), and B lines (21.5%).

Discussion

Plant growth and metabolism often depend on genetic potential and the surrounding environment. Thus, it is an interaction between G (genotype) and E (environment), which is difficult to separate as environmental conditions are subject to the prevailing weather conditions in a climatic zone. The relative contribution of G, E, and G × E effects under field conditions is much more difficult to decipher due to the vast variation in edaphic, environmental, and other factors. Among the nutrient factors is N, one of the major elements known to exert tremendous influence on plant growth and yield. In addition, the prohibitive costs of production, volatility, and leaching have negative roles, as the element plays a key role in rice crop productivity (Singh et al 1998, Samonte et al 2006). Under changing climate, managing N could play a pivotal role in rice crop production and productivity. In this context, the prerequisite is understanding the relationship between environment and genetic potential: lines grown without application of N brought out the variation that is due to genetic background. A wide variation in morpho-physiological characters was evident in these lines as evidenced from Tables 1–3. The addition of N enhanced growth and development to varying degrees (G × E interaction) over the N amount. The results were in tune with earlier observations that N resulted in an improvement in morphological characters and thereby induced the plant to produce more yield. However, when analyzed criti-

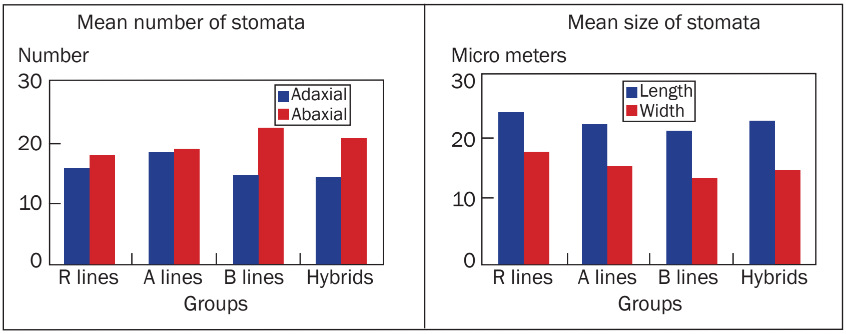

Fig. 4. Mean stomatal number, length, and width in parental lines and hybrids.

cally, that is, % change in response due to N application, none of the hybrids had a response similar to that of restorer, A, or B lines, indicating that some traits are not yet fully transmitted to the offspring, though hybrids had heterosis. It can be observed that, in some responses, hybrids were similar to either of the characters while in some they were moderate or altogether different. For instance, all the parental lines were much taller than under an N 0 environment but their physiological response to N application was much superior to that of hybrids. The morphologically dwarf nature of hybrids helps the plants to overcome lodging, which was not seen in parental lines. It appears that a reduction in plant height in the offspring (hybrids) modified and was compensated by enhanced production of tillers and effective booting tillers. Similarly, another interesting feature observed was leaf temperature in parental lines and hybrids. Leaf temperature maintenance, a lower % reduction in leaf area under N stress, and an increase in chlorophyll content as a result of N application in hybrids, even though moderate, helped to overcome adverse conditions. Transmission and expression of some of these characters, particularly a lower reduction in leaf temperature (hybrids had a cooler leaf temperature), was related to overcoming adverse environmental conditions through maintenance of better water retention characteristics. Further evidence in terms of stomatal number, width, length, etc., also corroborates the observation of lower leaf temperature and leaf rolling behavior under N stress. This might be one of the reasons for the yield superiority of hybrids. However, it can be noticed that all the genetic potential observed under the N 0 treatment was not fully transmitted to the hybrids, indicating a possibility for further yield improvement.

The amount of nitrogen taken up by the plant during the vegetative stage will determine leaf area (Fageria et al 1997a, Fageria 2007) and the radiation load the plant is able to take up under environmental stress. Ambient temperatures above 40 °C are detrimental at the reproductive stage with reference to development. A rise in leaf temperature in the plant, with a higher heat load due to increased surface area, results in higher leaf transpiration rates. This, in turn, depends on leaf stomatal density (Kadioglu and Terzi, 2007). A loss of moisture from the leaf through transpiration, high air temperature, and sunlight leads to the constriction of bulliform cells, which results in leaf rolling (Kadioglu and Terzi, 2007). In rice, this is dependent on specialized cells, called bulliform cells, present in the upper epidermis of the leaf (O'Toole and Cruz 1979, Kadioglu and Terzi 2007).

Losing much water through transpiration is not beneficial to plants. Hence, water-retaining characters will become crucial under increasing ambient temperature, which again depends on stomatal distribution of the leaf. The length and width of stomata varied in parental lines and hybrids. Hybrids have a moderate number of stomata, suggesting more water-retaining characters. These are further aided by the higher straw and grain nitrogen contents for a buildup of chlorophyll concentration in the tissues. An increase in leaf thickness raises the potential number of parenchymatous tissue layers, and a greater number of thicker leaves have enhanced photosynthetic activity (Li Jinwen et al 2009, Peng et al 2008) and, if combined with genetic potential, encourage yield.

Based on the results obtained with and without nitrogen application, irrespective of genotypes, treatments, and percent changes, hybrids had superiority and adapted well to (N) stress conditions. The genetic potential of the parental lines has not yet been completely transferred or expressed in their morpho-physiological response. This shows a possibility to further enhance the physiological response. However, the superiority of the hybrids in leaf temperature and water retention characteristics appeared to be more influenced by restorers and identifying parental lines with high N-use efficiency needs to be done further to develop climate-resilient hybrids with better productivity.

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Risk control of two-line hybrid rice seed production

Chengshu Zhou

The planting area of two-line hybrid rice has expanded rapidly since 2005, when the technique of risk control of two-line hybrid rice seed production was taking effect.

Up to 2010, two-line hybrid rice seed production occupied 25% of the total hybrid rice seed area. In commercial cultivation, the top three were two-line hybrids according to planting area.

The risk of two-line hybrid rice seed production mainly included the thermo-sensitivity of TGMS lines (S lines), the genetic drift of critical temperature (CT), isomorphic fertile plants, and the influence of abnormally low temperature occurring during the sensitive stage of S lines. Technical measures to control risk were as follows: using S lines with lower CT, strictly following the rules to produce S-line core seed and foundation seed, adopting technical measures for high yield and high-quality seeds, increasing S lines, selecting a favorable site as the seed base and favorable season for safe fertility expression and flowering, applying normative cultivation techniques to develop a uniformly female population, monitoring the sterility of S lines in fields, and predicting purity of the produced seed before harvesting.

Keywords: two-line hybrid rice, thermo-sensitivity, seed production, risk control

Using photo-thermosensitive genetic male sterility to develop S (sterile) lines used for making hybrid rice in China started in 1986 and found success in 1995. According to data from the Chinese Ministry of Agriculture, 3.5 million hectares were covered by two-line hybrid rice in 2010 and, based on planting area, among the top 10 varieties, 5 of them, and the top 3, were two-line hybrids (Table 1).

After more than 10 years' study and practice, the two-line hybrid rice seed production system was gaining perfection and production risk coming under control. The area of two-line hybrid rice seed production expanded fast starting in 2005 and reached 25,000 hectares in 2010, with an average yield of 2 t/ha, and the highest yield reached 4.22 t/ha in 2011. Up to 2011, two-line hybrid rice seed production represented about 25% of the total seed area.

Two-line hybrid rice seed production faces the following risks.

Table 1. Annual two-line hybrid rice planting area.

Year	Hybrid rice		Two-line hybrid rice			Remark
	Number of varieties	Total area (10,000 ha)	Number of varieties	Total area	%	
2010	499	1,448.4	75	351.2	24.2	Among the top 10 varieties, 5 of them, and the top 3, were two-line hybrids.
2009	490	1,556.7	54	281.8	18.1	Among the top 10 varieties, 5 of them, and the top 4, were two-line hybrids.
2008	484	1,595.7	49	269.9	16.9	Among the top 10 varieties, 4 of them, and the top 2, were two-line hybrids.
2007	432	1,466.3	31	230.9	15.7	Among the top 10 varieties, 4 of them, and the top one, were two-line hybrids.
2006	458	1,519.9	28	212.7	14.0	Among the top 10 varieties, 3 of them, and the top one, were two-line hybrids.
2005	379	1,495.1	27	135.9	9.1	Among the top 10 varieties, 2 of them, and the top one, were two-line hybrids.
2004	267	1,463.7	15	115.9	7.9	Among the top 10 varieties, 1 of them, and the first one, was a two-line hybrid.
2003	243	1,322.3	9	87.4	6.6	
2002	228	1,431.1	9	123.7	8.6	
2001	223	1,570.6	11	116.7	7.4	Among the top 10 varieties, 1 of them, and the third one, was a two-line hybrid.
2000	216	1,372.7	8	103.5	7.5	Among the top 10 varieties, 1 of them, and the seventh one, was a two-line hybrid.
1999	190	1,392.3	5	81.2	5.8	
1998	189	1,520.3	4	43.1	2.8	
1997	168	1,531.6	3	17.7	1.2	
1996	133	1,463.6	4	4.5	0.3	
1995	119	1,345.6	1	0.9	0.1	

Table 2. The critical temperature (CT) of the main S lines currently used in China.

S line	CT (°C)	S line	CT (°C)
PA64S	23.3	ZhunS	24.0
Guangzhan63S	24.0	Zhu 1S	22.6
Y58S	23.5	LU 18S	23.0
P88S	24.0	Xiangling 628S	23.0
C815S	23.5		

1.1 Thermo-sensitivity of fertility expression of S lines

At present, all S lines used for two-line hybrid rice production belong to the high temperature-inducing male sterility type, and fertility conversion is regulated by environment temperature (Table 2). An S line is made sterile under a higher temperature and can then be used for seed production, and it becomes fertile under a lower temperature environment, for use in seed increase. The threshold temperature of fertility conversion is also called the critical temperature (CT).

1.2 CT genetic drift

The CT of S lines could rise after seed increase for two to three generations, which is also called CT genetic drift. For example, PA64S was an S line with a CT of 23.3 °C in 1991 when it was just released and was identified with a CT of 24.2 °C after increasing for three generations. When the CT was higher, the risk in seed production was higher.

1.3 Bio-mixtures during seed increase and isomorphic fertile plants

During seed increase, S lines were partially fertile after being treated with lower temperature at the sensitive stage, which is about 12 to 18 days before flowering. Sterile spikelets could be contaminated by external pollen due to improper isolation.

When the contaminated seed was increased for two to three generations, some isomorphic fertile plants were mixed in S line populations because manual roguing was done according to morphological traits; thus, the isomorphic plants were difficult to eliminate from fields. Thus, those plants could reduce seed purity.

1.4 Inappropriate cultivation could cause the sensitive stage to go out of the expected safe period.

A delay in seedling transplanting, inappropriate fertilizer application and irrigation, and stagnant seedlings could lead to the sensitive stage and flowering time going beyond the expected safe period and increase the risk of low-temperature influence.

1.5 Techniques of risk control of two-line hybrid rice seed production

Two-line and three-line hybrid rice seed production basically had the same technical principles and methods, with the key differences being ensuring stable sterility and monitoring fertility in fields.

2.1 Adopted S lines with lower CT

The S lines currently used in China had CT from 22.5 to 23.5 °C and, by using these kinds of S lines, site selection for a seed base could be wider and sterility safety could be higher.

2.2 Core seed and foundation seed production and restricting the increasing generations of foundation seed

The main purpose of core seed production is to stabilize CT and eliminate isomorphic fertile plants. Plants with typical morphological traits of the S line are selected and treated with temperature by the standard CT of the S line**.** The plants with partial sterility are cut and then the ratooned plants are treated with temperature lower than the standard CT to obtain the core seeds. The harvested core seeds are planted in lines and treated with lower temperature during the sensitive stage along with inspection of morphological traits during tillering, flowering, and maturing stage. Off-types are rogued. Seeds are bulk-harvested from all lines to obtain the foundation seeds and limited increasing is done within two generations before using them for seed production.

2.3 Increase S lines with high yield and high quality

Two cold sources can be used for S line seed increase: cold water and lower temperature.

1. Cold-water irrigation: Fields are selected with sufficient cold-water supply and with temperature around 19–21 °C. The field water temperature is maintained at 22–23 °C during the sensitive stage, with depth about 5 cm higher than the tip of the young panicles. The period of cold-water irrigation is about 15 days.
2. Cold season (winter) planting: This involves planting S lines in the southern part of Hainan Province (17°N) during the winter season, with the sensitive stage at the end of January to early February when the temperature is the lowest. This method is economical but yield is not stable due to abnormal weather changes.
3. Highland planting: A location at high altitude with cool temperature is suitable for S line seed increase. A study using weather data of multi-years revealed that locations at about 1,500 m in Yunnan Province (23°N) with daily temperature of about 22 °C during July and August were suitable for S line increase. Y58S was planted there in 2010 and 2011, and the average seed yield was 4.5 t/ha and the highest was 7.5 t/ha.

There were three key points for maintaining seed purity:

1. The seeds used for increase come from core seeds or foundation seeds within less than two generations of increase.
2. The seed field is strictly isolated.
3. Rogue frequently from planting to harvesting, especially during tillering, before and at heading, and before harvesting.

2.4 Select favorable environments for two-line hybrid rice seed production

Two-line hybrid rice seed production needs to have a favorable site as a seed base and a favorable season to ensure stable male sterility.

The selection of favorable environments is based on the CT of S lines and analysis of the weather data of multiple years to get a safe fertility index.

We collected all accumulated weather data for the seed base, and found out the years that had continuous temperature lower than the CT of S lines for more than 3 days during the expected fertility sensitive stage. The formula for safe fertility index is as follows:

$$\text{Safe fertility index} = 1 - \frac{\text{Sum of years that had low temperature during fertility sensitive stage}}{\text{All years in which data were collected}}$$

Index = 1: favorable for two-line hybrid rice seed production.
Index ≥0.95≤1: area limited to reduce risk.
Index ≤0.95: not suitable for two-line hybrid rice seed production.

2.5 Cultivate a uniform S line population

A uniform S line population could shorten the sensitive period of the population and ensure seed purity. To increase the quality of S line seed, low seeding density is maintained in a nursery for raising vigorous seedlings. Plants are transplanted in time, and topdressed fertilizer is used earlier. Less nitrogen fertilizer is used at the middle and late growth stage to control late tillers.

2.6 S line fertility monitoring in fields and estimating seed purity

The male sterility of S lines could be influenced by unexpected weather changes and differences in micro-environments between seed bases or plants with higher CT. In that case, sterility should be monitored to check stability and seeds should be inspected for purity before harvesting.

1. Fertility monitoring methods:
   Temperature analysis: Check temperature data against the CT of the S line during the S line sensitive stage, especially when cold air occurs.
   Anther and pollen observation: Observe the appearance of anthers visually and check pollen fertility under a microscope to ensure that male sterility is stable.
   Isolated planting: Take sample plants of S lines from seed fields randomly and grow them in a strictly isolated place to check selfed seed-setting.
2. Formula for estimating seed purity:
   The purity of produced seed could be estimated based on the data collected from fields, including the selfed seed-setting obtained from isolated grown plants, the outcrossed seed-setting from seed fields, and the percentage of off-types obtained from the seed fields:

$$X\ (\%) = 100 - \left(a + \frac{n}{m} \times 100\right)$$

X: estimated seed purity (%);
a: off-type plant (%), data form field investigation;
n: selfed seed-setting rate (%), data from isolated growing plants;
m: outcrossed seed-setting rate (%), data from field investigation.

Identifying suitable areas for hybrid rice seed production

B. Sailaja, S.R. Voleti, A.S. Hariprasad, L.V. Subba Rao, and B.C. Viraktamath

Hybrid rice is one of the proven technologies for enhancing rice production and productivity. The timely availability of good-quality hybrid seed is one of the prerequisites for the large-scale adoption of hybrid rice. Seed yields depend on various factors such as season, location, parental lines involved, row ratio, extent of synchronization of flowering of parents, supplementary pollination, etc. An attempt is made to find the most appropriate locations across the country with prevailing climatic conditions under which hybrid seed production is already going on. In India, the dry (rabi) season (November-April) has been found to be better than the wet (kharif) season (June-October) for hybrid seed production. Prevailing locations for hybrid seed production such as Warangal, Mandya, Erode, and Coimbatore are examined for ascertaining local weather requirements. Grid-wise weather data on maximum, minimum, and mean temperatures and rainfall were collected from IMD for 1995-2005. Thessien polygons were generated for each point using the spatial interpolation method of the ArcGIS package. This map was overlaid with a district-level digital database of India. District-wise data on maximum, minimum, and mean temperatures and differences in day and night temperatures were computed. Because of the nonavailability of grid-wise data for other parameters such as relative humidity and wind speed, daily normal data were downloaded from the IMD Web site. Finally, suitable areas for hybrid seed production were identified by filtering districts for favorable conditions during flowering time in the rabi and kharif seasons.

Rice is the most important food crop in developing countries and it plays a key role in delivering global food security. The Green Revolution in rice farming of the late 1960s denotes the beginning of the extensive breeding programs that have led to the many improved rice varieties that are now planted on more than 60% of the world's rice land. This revolution led to increases in yield potential of two to three times that of traditional varieties (Khush 1987). However, in view of the continued population growth, demand for rice is expected to be 120–130 million tons by 2025. Despite significant investments in rice research, more than 50% of the rice-growing districts have lower yields than the national average (Rice in India 2006). Even after the advent of high yield technology, a sizable area, including irrigated area, is categorized as low production. Yield gap analysis reveals that 30% to 40% of the potential yield is yet to be tapped with available high-yielding varieties (HYVs) sown on highly productive irrigated soils. The plateauing trend in the yield of HYVs, declining and degrading natural resources such as land and water, and the acute shortage of labor make the task of increasing rice production quite challenging.

Hybrid rice is one of the technologies proven to enhance rice production and productivity. China has developed and perfected hybrid seed production over the years. The success of hybrid rice depends primarily on the availability of heterotic hybrids, efficient and economic hybrid seed production, and effective technology transfer efforts. The timely availability of good-quality hybrid seed is therefore one of the prerequisites for the large-scale adoption of hybrid rice, and a high priority for the popularization of rice hybrids to obtain food security.

Rice is basically a self-pollinated crop, for which the extent of natural outcrossing is only 0.3% to 3.0%. Therefore, hybrid rice seed production requires specialized techniques that need to be thoroughly understood before embarking on the venture. The main objective in hybrid rice seed production is to obtain maximum seed set in female lines so that seed yields are higher. Seed yields depend on various factors such as season, location, parental lines involved, row ratio, the extent of synchronization, supplementary pollination, etc. This chapter aims to study the climatic conditions in different locations where hybrid rice has already been grown and similar conditions prevail in the wet (kharif) and dry (rabi) seasons so as to take up hybrid seed production at locations other than the existing ones.

In India, the rabi season (November-April) has been found to be better than the kharif season (June-October) for hybrid seed production. Seed yields are almost twice as high in the rabi season as in the kharif season. So, most large-scale seed production in India occurs in southern India during the rabi season. Seed yields are adversely affected if the temperatures during flowering time are below 20 °C or above 35 °C or if there is a rainy spell of more than 3 to 4 days at the time of flowering and pollination.

As per the literature available, the ideal conditions for hybrid rice seed production are daily mean temperature of 24–30 °C, relative humidity of 70–80%, diurnal differences of 8–10 °C, sunlight bright but not cloudy, moderate wind velocity (8–10 km/h), and no continuous rainfall for 3 days during flowering. Thus, locations for seed production should be selected, taking into consideration all these seasonal conditions.

Methodology

February and March for rabi and August and September for kharif seasons are favorable for peak flowering time. Based on the favorable seasonal conditions, different locations were screened for suitability of hybrid seed production. The process for identifying probable locations was divided into two parts:

- Ascertaining the local weather requirement for hybrid seed production.
- Extending these conditions to predict and identify alternate locations for hybrid seed production.

Ascertaining local weather requirements for hybrid seed production

Since the dry season in Karimnagar and Warangal districts of Andhra Pradesh, India, is the most ideal for hybrid rice seed production, weather data from Warangal District were analyzed and used for identifying alternate locations suitable for hybrid seed production. Also, Karimnagar, Coimbotore, Mandya, Kolhapur, and some other districts were examined with 2008 and 2009 weather data for confirmation. Daily weather parameters of Warangal District for February and March were collected from AICRIP data sets for 1990-2005. These data were tested for the above favorable seasonal conditions. A model was developed for computing day and night temperatures by using that proposed by Bouman et al (2001).

Hourly temperature (Td) = (Tmin + Tmax)/2 + (Tmax+Tmin) * cos (0.2618 * (h – 14))/2 – (1) was determined where Tmin and Tmax are minimum and maximum temperatures and h is the time of day. These temperatures were averaged on a 12-hour basis and the differences in day and night temperatures were computed.

Extending these conditions to predict and identify alternate locations for hybrid seed production

Grid-wise weather data on maximum, minimum, and mean temperatures and rainfall were collected from IMD for 1995-2005 (Fig. 1). Year-wise individual text files were supplied for each parameter. A software program was developed to convert these individual text files into a centralized database.

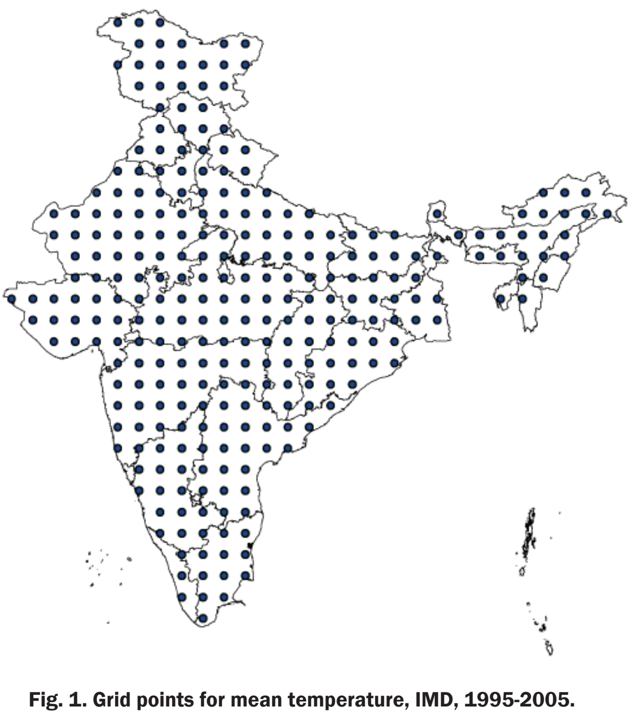

Fig. 1. Grid points for mean temperature, IMD, 1995-2005.

There were a total of 346 grid points for temperature and 960 points for rainfall (Fig. 1). These files were converted to geo database files using Arc Catalog, and Thessien polygons were generated for each point using the spatial interpolation method of the ArcGIS package. District-wise data on maximum, minimum, and mean temperatures and differences in day and night temperatures were computed over polygons.

Because of the non-availability of grid-wise data for other parameters such as relative humidity and wind speed, daily normal data were downloaded from the IMD Web site. These data were arranged in the database format. These two data sets were joined for each district and organized on a weekly basis for February and March during rabi and August and September during kharif.

Furthermore, these weather data were joined with digital data of India at the district level (Survey of India, 2010). Maps were generated for each week in the respective months for mean temperature, differences in day and night temperature, relative humidity, and rainfall. These digital data of the overlaid map were queried further for favorable weather conditions.

Results and discussion

Ascertaining local weather requirements for hybrid seed production

Weekly weather data from Warangal District for a 15-year period were consolidated and each parameter was verified for favorable seasonal conditions for hybrid rice seed production during the flowering period in the rabi season. The parameters are shown in Table 1. Mean temperatures for 4 weeks of February and March are in the range of 25–30 °C and the differences in day and night temperatures are in the range of 9–10 °C. Rainfall is within the range of 0–2.2 mm for these 8 weeks. These three parameters confirm the favorable seasonal conditions mentioned above. Relative humidity (average of RH1 and RH2) is in the range of 55–67%. RH1 is within the range of 70–80%, confirming the requirements of favorable RH for hybrid seed production (Table 1). This allows us to extend the weather for other locations and the results obtained are as follows.

Table 1. Weekly weather data from Warangal District, averaged for 15 years.

Month	Week	RH1 (%)	RH2 (%)	RH (%)	Mean temp. (°C)	Difference in day and night temperatures (°C)	Rainfall (mm)
2	1	84.50	49.7	67.1	25.4	10.0	2.2
2	2	81.86	41.3	61.6	26.1	9.8	0.6
2	3	79.27	40.0	59.6	26.8	10.4	0.7
2	4	75.10	40.3	57.7	29.1	9.7	0.0
3	1	75.73	42.0	58.9	30.6	9.8	0.0
3	2	76.86	39.4	58.2	29.3	10.2	0.1
3	3	75.83	35.5	55.7	28.7	10.9	0.2
3	4	78.02	39.3	58.6	30.5	10.8	0.4

Extending these conditions to predict and identify alternate locations for hybrid seed production

Based on grid-based data of temperatures, districts were filtered for favorable mean temperature (25–30 °C) and differences between day and night temperatures (5–10 °C). Also, Warangal District data were compared with kharif data from a few other locations using IMD data. It was observed from the weather conditions of Warangal district that relative humidity is within 55–67% in the rabi season and within 70–80% in the kharif season and wind speed is within 1–3 m/s. Every district was tested for prevailing weather scenarios identical to those of Warangal District week-wise, especially in the flowering period for both the rabi and kharif seasons. Further, districts matching with favorable conditions for 7–8, 5–6, 3–4, and 2 weeks were considered as potential areas and presented in Figures 2 to 8.

It is clear from Figure 2 that all the districts from the southern states of Andhra Pradesh, Tamil Nadu, Karnataka, and Kerala and a few districts from Odisha, Chattisgarh, Gujarat, Maharashtra, and West Bengal (Fig. 2) match with the favorable mean temperatures (25–30 °C) and day and night temperatures (5–10 °C) continuously for more than 4 weeks during flowering time (February and March) of the rabi season.

During the kharif season, the scenario of similar weather prevailing during flowering time varied. For instance, in the kharif season (August and September), few districts

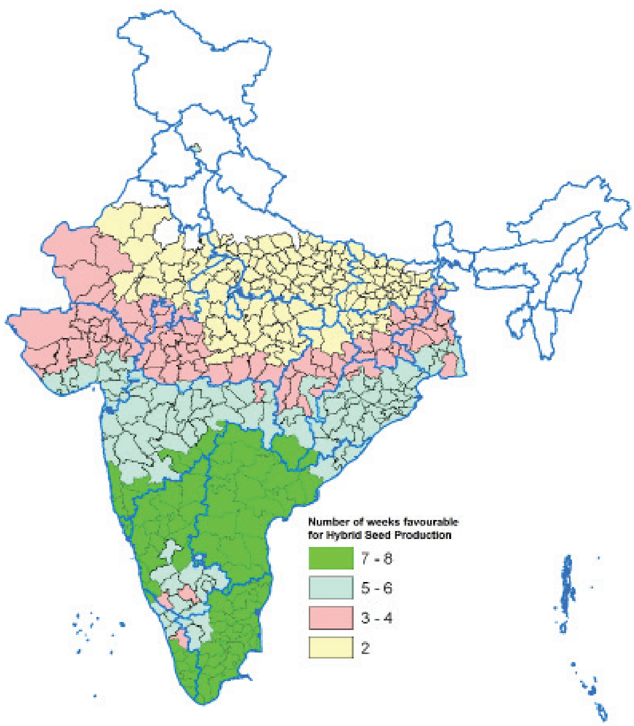

Fig. 2. Districts matching with the favorable temperature range (25–30 °C) for hybrid seed production during flowering time in the rabi (dry) season.

from Andhra Pradesh, Tamil Nadu, Karnataka, Haryana, Punjab, and Rajasthan (Fig. 3) match with the favorable mean and difference in day and night temperatures for more than 4 weeks. Furthermore, these districts were filtered for rainfall suitable for hybrid seed production.

All the districts matching for favorable temperature also meet the rainfall requirement (0 -10 mm) for hybrid seed production during the flowering period for more than 4 weeks in the rabi season (Fig. 4).

In the kharif season, only 13 districts covering Tamil Nadu, Karnataka, Punjab, and Haryana have zero rainfall and almost all the districts have a similar temperature range and rainfall requirement (0–3 mm) for more than 4 weeks during the flowering period (Figs. 5A and 5B).

These districts were further filtered to check for other weather parameters such as relative humidity and wind speed along with the above weather parameters during flowering time. It is observed from the weather conditions of Warangal district that relative humidity is within 55–65% in the rabi season and within 70–80% in the kharif season and wind speed is within 1–3 m/s. These districts were further filtered for these conditions.

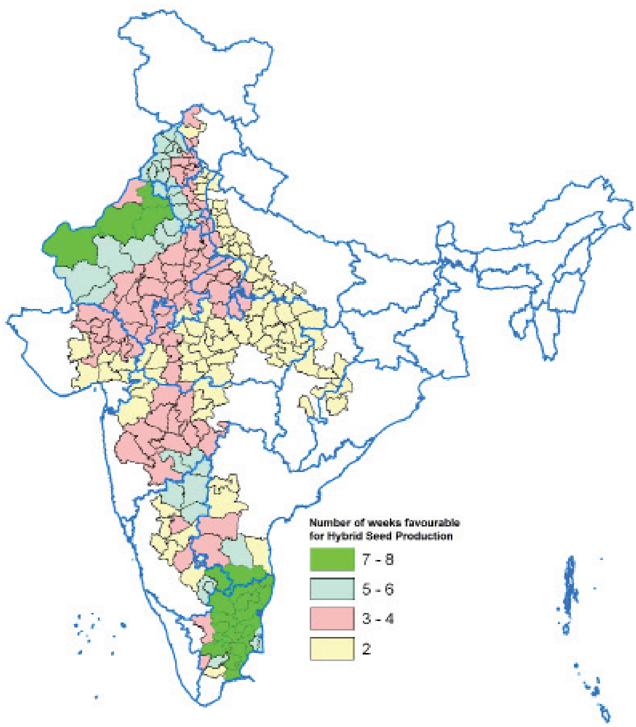

Fig. 3. Districts matching with the favorable mean temperature range (25–30 °C) for hybrid seed production during flowering time in the kharif (wet) season.

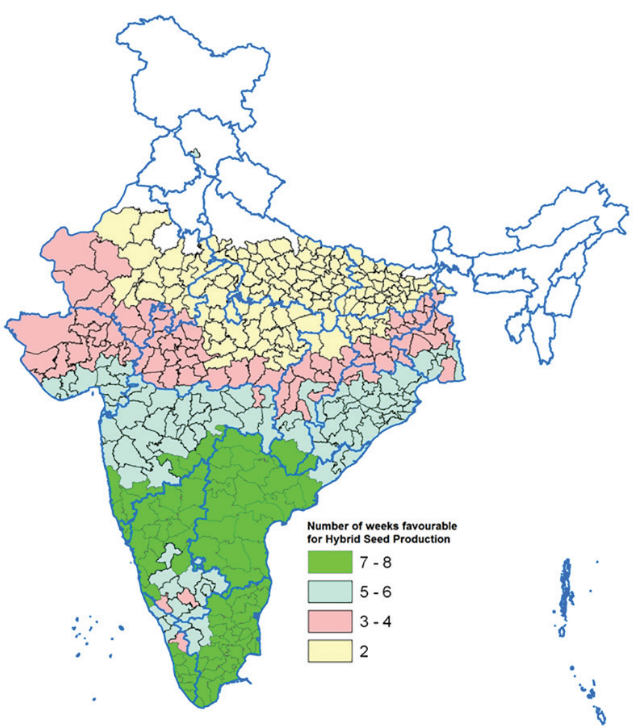

Fig. 4. Districts matching with the favorable mean temperature (25–30 °C), day and night temperature (5-100 °C) and rainfall range (0–10 mm) for hybrid seed production during flowering time in the rabi (dry) season.

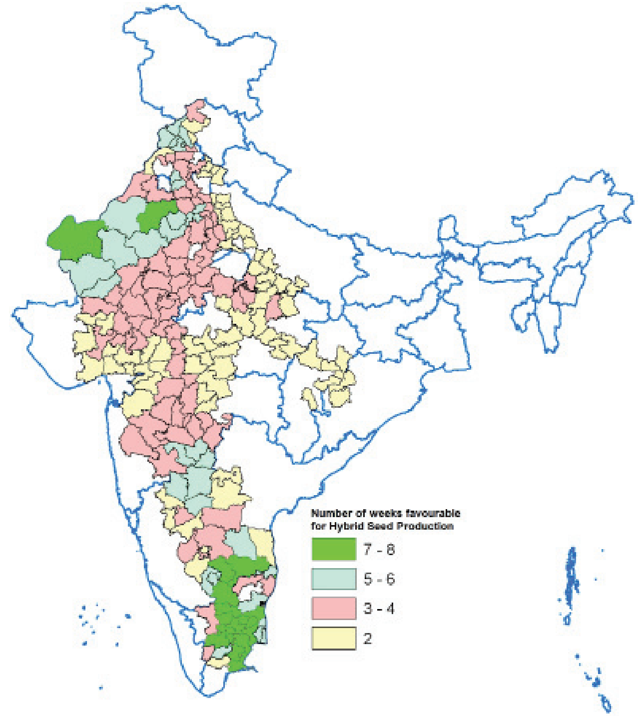

Fig. 5A. Districts matching with the favorable mean temperature (25–30 °C), day and night temperature (5–100 °C) and rainfall range (0–3 mm) for hybrid seed production during flowering time in the kharif (wet) season.

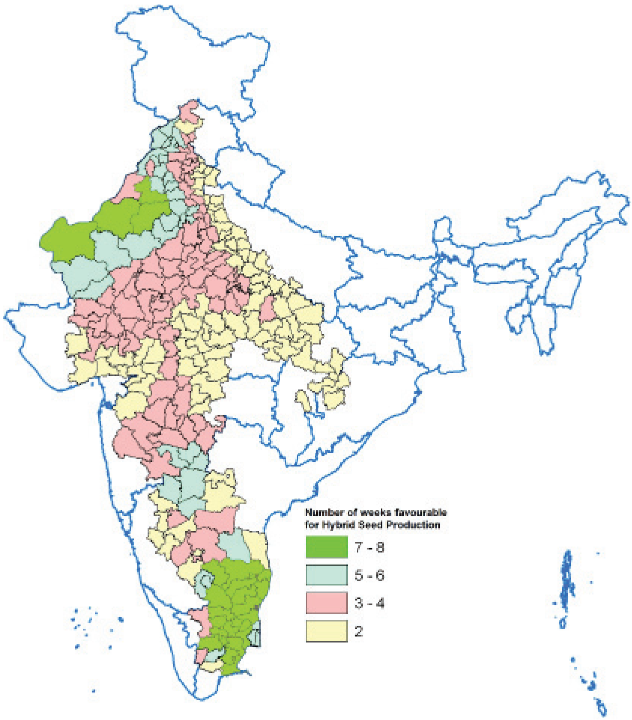

Fig. 5B. Districts matching with the favorable mean temperature (25–30 °C), day and night temperature (5–100 °C) and rainfall range (0–10 mm) for hybrid seed production during flowering time in the kharif (wet) season.

Only six districts—Haveri and Udipi (Karnataka) and Madhurai, Dharmapuri, Tiruvannamalai and Vellore (Tamil Nadu) match with the favorable conditions of Warangal for all 8 weeks and, in total, 40 districts have greater than 4 weeks in the rabi season (Fig. 6). Many districts appearing to be adequate for temperature and rainfall do not meet the RH and WS values required for hybrid seed production.

Only one district, Namakkal (Tamil Nadu), matches with the above-listed favorable conditions (RH = 70–80%; rainfall = 0–3 mm) of Warangal for all 8 weeks and eight districts—Bijapur (Karnataka); Karur, Nagapattanam, Namakkal, Ramanathapuram, Sivaganga, and Villupuram (Tamil Nadu); and Hosiarpur and Jalandhar from Punjab (Fig. 7A and 7B) match for more than 4 weeks in the kharif season.

Finally, weather conditions prevailing during 7-8 weeks each in the rabi and kharif seasons were used to determine the suitability of a given location for hybrid rice seed production. Based on these comparisons, suitable districts for both rabi and kharif seasons are listed in Tables 2 and 3.

This preliminary study revealed that, for the rabi season, as many as 13 districts in 6 states are most ideal for hybrid rice seed production. However, other factors such as availability of adequate water and labor and other logistics have to be worked out, including the training of seed growers. Many districts are found suitable with less

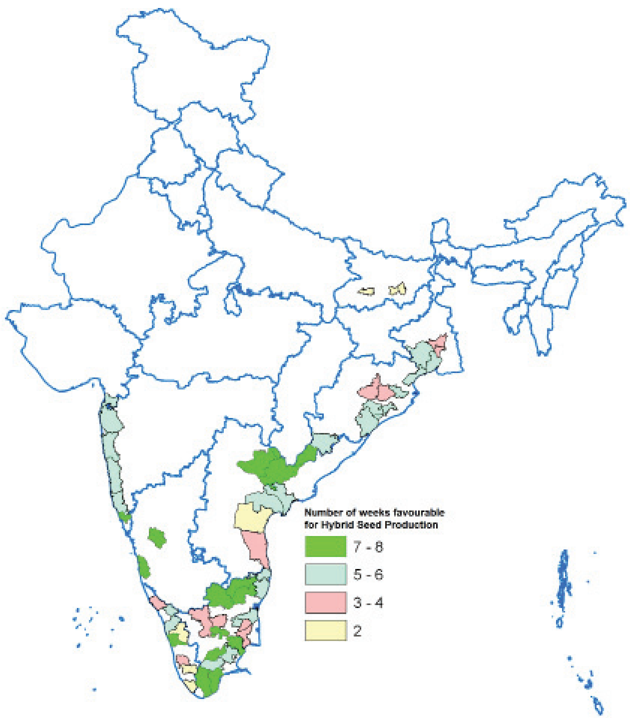

Fig. 6. Districts matching with the favorable mean temperature (25–30 °C), day and night temperature (5–100 °C), rainfall range (0–10 mm), RH (55–65%) and wind speed (0–3 m/s) for hybrid seed production during flowering time in the rabi season.

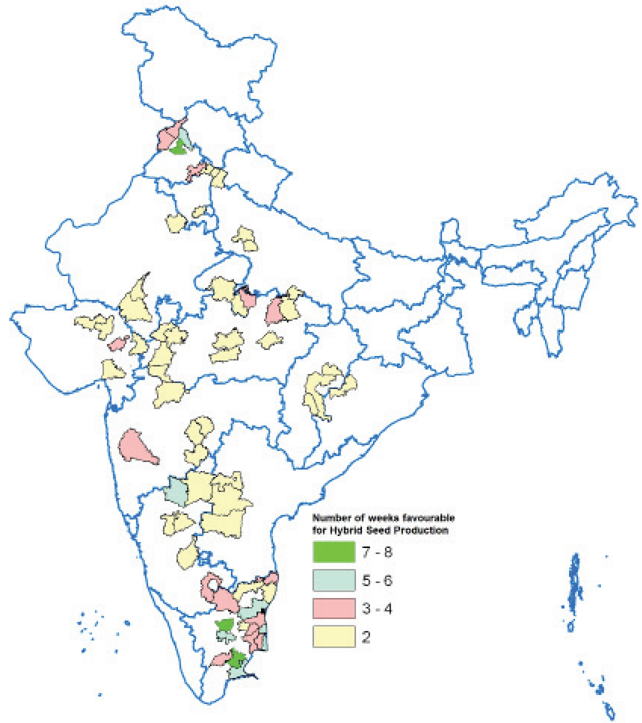

Fig. 7A. Districts matching with the favorable mean temperature (25–30 °C), day and night temperature (5–100 °C), rainfall range (0–10 mm), RH (70–80%) and wind speed (0–3 m/s) for hybrid seed production during flowering time in the kharif season.

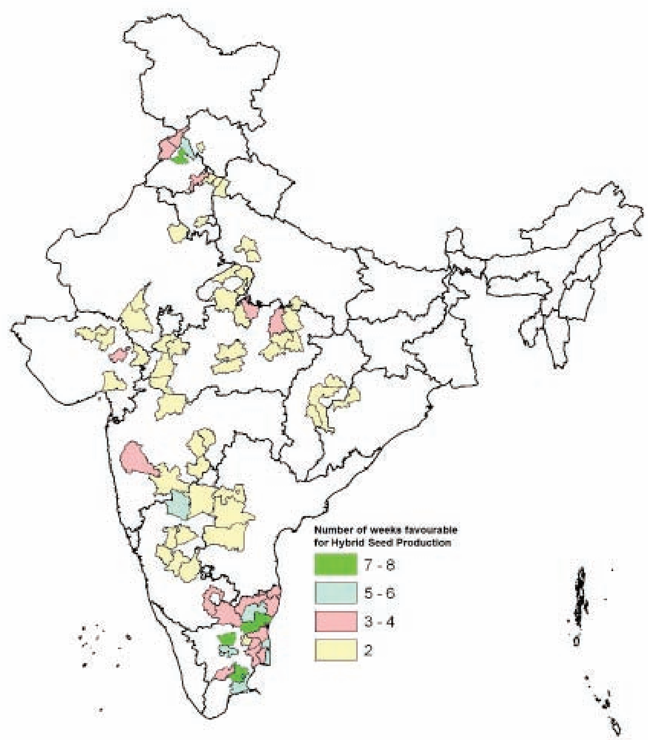

Fig. 7B. Districts matching with the favorable mean temperature (25–30 °C), day and night temperature (5-100 °C), rainfall range (0–10 mm), RH (70–80%) and wind speed (0–10 m/s) for hybrid seed production during flowering time in the kharif season.

than 6 favorable weeks and, with minor adjustments, hybrid seed production can be taken up successfully.

The study revealed that few districts are suitable for hybrid rice seed production compared to the rabi season, reiterating the fact that the dry season is best for successful hybrid rice seed production. Higher rainfall and humidity, cloudiness, and lower wind velocity affect seed yield during the kharif season. However, only four districts (Namakkal, Villupuram, and Sivaganga in Tamil Nadu and Jalandhar in Punjab) were found ideal with favorable weather conditions prevailing for 7–8 weeks. Many districts showed promise but with a narrow window of favorable weather prevailing for 4 weeks and less than 4 weeks.

This is a first-of-its-kind preliminary study wherein IMD and GIS data have been used to identify suitable alternate sites for hybrid rice seed production. Further analysis, fine tuning, and critical evaluation from all other angles are needed before going to pilot seed production activities in selected areas.

Table 2. Alternate sites suitable for hybrid rice seed production based on favorable weather data (using Warangal data as base).

	Rabi (dry) season
No. of favorable weeks during flowering (February and March)	States (districts)
7–8	Andhra Pradesh: Khammam Goa: North Goa Karnataka: Haveri, Udupi Kerala Trishshur Odisha: Malkangiri Tamil Nadu: Dharmapuri, Madurai, Tiruvannamalai, Vellore, Karur, Pudukkottai: Tirunelveli, Tuticorin (Tuttukudi)
5–6	Andhra Pradesh: Guntur, Krishna Gujarat: Valsad Kerala: Malappuram, Wayanad Maharashtra: Mumbai City, Ratnagiri, Raigad, Sindhudurg, Thane Odisha: Baleshwar, Jajapur, Koraput, Nayagarh, Ganjam, Khordha Tamil Nadu: Cuddalore, Kanchipuram, Perambalur, Virudunagar, Sivaganga, Tiruvallur West Bengal: Kolkata, Pashchim Medinipur, Purba Medinipur
3–4	Andhra Pradesh: Nellore Kerala: Kannur, Kottayam Odisha: Anugul, Dhenkanal Tamil Nadu: Ariyalur, Erode, Namakkal, Thanjavur West Bengal: Haora, Hugli
2	Andhra Pradesh: Prakasam Bihar: Jhanabad, Lakhisarai, Munger Kerala: Palakkad, Pattanamtitta, Thiruvananthapuram

Favorable weather conditions: Mean temp: 25–30 °C; difference in day and night temp: 5–10 °C; RH: 55–70%; rainfall = 0–10 mm

	Kharif (wet) season
No. of favorable weeks during flowering (August and September)	States (districts)
7–8	Punjab: Jalandhar Tamil Nadu: Namakkal, Villupuram, Sivaganga
5–6	Karnataka: Bijapur Punjab: Hoshiarpur Tamil Nadu: Karur, Nagappattinam, Ramanathapuram, Tiruvannamalai
3–4	Karnataka: Bangalore rural Madhya Pradesh: Panna Punjab: Amritsar, Gurdaspur, Patiala Punjab: Amritsar, Gurdaspur, Patiala Tamil Nadu: Chennai, Cuddalore, Thiruvarur Gujarat: Kheda Madhya Pradesh: Tikamgarh Maharashtra: Pune Tamil Nadu: Ariyalur, Dharmapuri, Kanchipuram, Madurai, Thanjavur, Tiruvallur, Vellore
2	Andhra Pradesh: Kurnool, Mahbubnagar, Rangareddy Chhattisgarh: Dhamtari, Janjgir, Champa, Raipur Gujarat: Bharuch, Dahod, Mahesana, Patan Haryana: Ambala, Jhajjar, Yamunanagar Himachal Pradesh: Hamirpur Karnataka: Chitradurga, Davangere, Gadag, Gulbarga, Haveri, Koppal Madhya Pradesh: Barwani, Bhind, Datia, Dhar, Hoshangabad, Jabalpur, Katni,Morena, Raisen, Ratlam, Satna, Shivpuri, Ujjain, Umaria Maharashtra: Hingoli, Jalgaon, Latur, Parbhani’ Solapur Odisha: Baragarh Rajasthan: Jhunjhunun, Raj Samand, Udaipur Tamil Nadu: Perambalur Uttar Pradesh: Banda, Chitrakoot, Etah, Lalitpur, Mainpuri, Saharanpur

Favorable weather conditions: Mean temp: 25–30 °C; difference in day and night temp: 5–10 °C; RH = 70–80%; rainfall: 0–10 mm

Table 3. Alternate promising areas suitable for large-scale hybrid seed production in the rabi season.

No. of favorable weeks during flowering (February and March)	States (districts)
7–8	A.P (Khammam), Karnataka (Kaveri, Udupi), North Goa, Tamil Nadu (Dharmapuri, Madurai, Tiruvnnamalai, Vellore, Karur, Pudukottai, Tirunelveli, Tullukudi), Kerala (Trissur)
5–6	Kerala (Malapuram), Odisha (Malkargiri, Baleshwar, Tajapur, Korput, Naya)

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Notes

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Frontline demonstrations on hybrid rice: current status and future prospects

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Frontline demonstrations are considered to be the most effective and useful extension activity to demonstrate the latest technologies developed at research stations to the ultimate clientele, that is, farmers, in their own fields. The principle of "seeing is believing" is operational in these demonstrations, as the farmers become easily convinced when they see the performance of new technologies in the fields of their neighboring farmers. The program on frontline demonstrations (FLDs) is formulated by the Indian Council of Agricultural Research (ICAR) and funded by the Ministry of Agriculture, government of India. Since the technology generators (scientists) are directly demonstrating and disseminating the research technologies in farmers' fields, they are called "front-line" demonstrations.

A comprehensive package consisting of new seed (variety/hybrid) and recommended cultivation and plant protection practices, etc., is demonstrated to farmers. Financial assistance is provided for critical inputs such as seed, fertilizer, weedicide, pesticide, etc. The unique feature of these demonstrations is the active involvement of concerned scientists for providing technical guidance from time to time and the active participation of farmers in implementing the recommended technologies. The organization of field days at an appropriate stage of the crop at strategic locations for a cluster of 20–30 demonstrations is an integral part of these demonstrations, which adds significantly to their effectiveness. These field days provide an on-the-spot opportunity for a large number of interested farmers to acquaint themselves with the advantages of the new technologies, to have their doubts clarified with subject matter specialists during question-and-answer sessions, and to meet the scientists and extension officials who are aware of the latest developments in agriculture. Overall, this approach has proved to be a very effective tool for the transfer of new technologies. The operational workflow for conducting these FLDs appears in Figure 1.

FLDs on hybrid rice: the beginning

Hybrid rice is an innovative technology that was introduced to Indian agriculture in 1994. Hybrids are expected to give 1.0 to 1.5 tons extra yield per hectare compared with high-yielding inbred varieties. Despite the distinct yield advantage, the large-scale adoption of hybrid rice in India was found to be slower than expected in the initial years. There were many reasons for this but perhaps one of the major reasons was

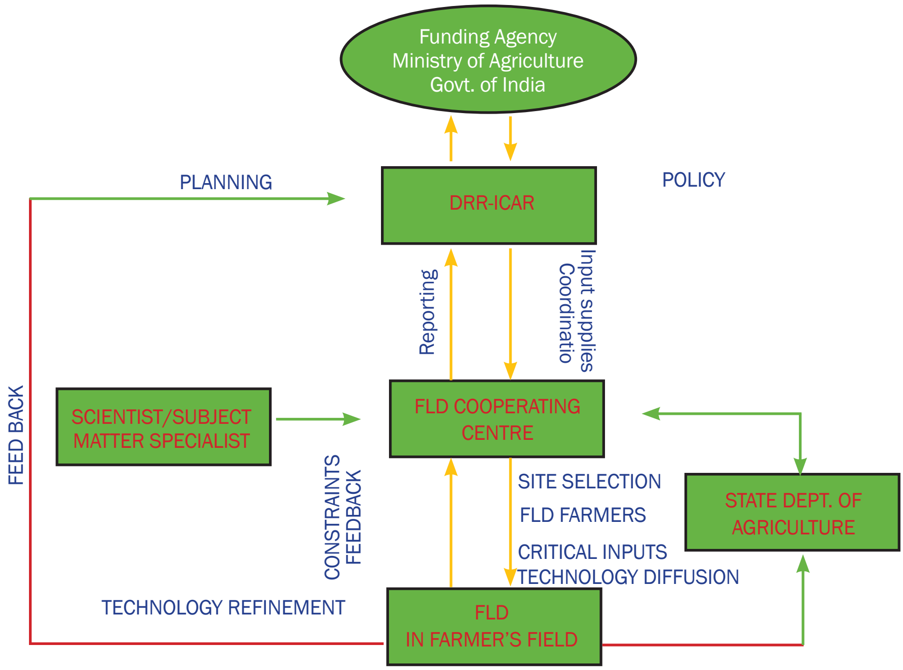

Fig. 1. Conceptual framework of the FLD program.

inadequate extension efforts to create awareness about the potential benefits of this innovative technology among rice farmers. The Directorate of Rice Research (DRR), Hyderabad, took the lead in initiating a national program on hybrid rice, coordinating and implementing the national program and developing the hybrids and seed production and cultivation packages, and had to take the lead again in popularizing this innovative technology. Despite the lack of a specific mandate in this respect, and lack of personnel and facilities, pioneering efforts have nevertheless been made by DRR to popularize this technology in the country. To begin with, a large number of compact block frontline demonstrations of released hybrids as well as demonstrations on seed production technology were organized in various states under the second phase of the United Nations Development Programme (UNDP) project during 1998-2002.

A large number of training programs on both hybrid rice seed production technology and hybrid rice cultivation were also organized for various clients of 1 to 7 days' duration by DRR as well as the research network centers. Special training programs were organized for farm women. Interstate exposure visits were organized for hybrid rice farmers and hybrid rice seed producers. Sensitization workshops were organized for senior research managers and policymakers.

After conclusion of the UNDP project, the frontline demonstrations on hybrids were continued under the National Agricultural Technology Project (NATP) of ICAR and, for the past 7 years, FLDs on hybrid rice have been organized under the macro-management scheme of the Ministry of Agriculture, government of India.

Technology outreach using FLDs: achievement in number

The FLD program on hybrid rice has two distinct phases. The first one comprised compact block demonstrations conducted as a part of the UNDP and NATP projects in which first-generation hybrids were demonstrated. The focus of these demonstrations was mainly on southern Indian states along with a few northern Indian states such as Uttar Pradesh, Uttarakhand, Haryana, and Punjab. The second phase of FLDs has witnessed a large number of second-generation hybrids making their way to new states such as Chhattisgarh, Bihar, Jharkhand, and Odisha.

Between 1998 and 2012 (14 years), a total of 12,001 FLDs of 1 hectare each were conducted covering all the major rice-growing states of the country. It is estimated that about 28,000 farmers directly benefited from these demonstrations along with thousands of farmers who became aware of hybrid rice technology. The trickle-down effects of the FLD program are many. State-wise hybrids demonstrated, the total area covered, and the yield advantages recorded appear in Table 1 and Figure 2.

In Uttar Pradesh, 2,876 demonstrations were conducted focusing on hybrids such as NSD-2, PSD-1, PSD-3, PA 6444, PHB-71, and KRH-2. Compared with the most popular high-yielding varieties (HYVs) in the state, these hybrids recorded yield advantages in the range of 850–2,215 kg/ha. Karnataka State conducted about 1,900 FLDs, whereas Maharashtra conducted 1,485 FLDs. Other states that have conducted FLDs on hybrids were Andhra Pradesh, Tamil Nadu, West Bengal, Odisha, Uttarakhand, Goa, Bihar, and Chhattisgarh. In most of the demonstrations, the yield advantages of hybrids were conspicuous and were in the range of 1 to 1.5 t/ha.

Table 1. Overview of FLDs conducted on hybrid rice (1998-2012).

State	Hybrids demonstrated	No. of FLDs (1 ha each)	Yield advantage (kg/ha)
Uttar Pradesh	NSD-2, PSD-1, PSD-3, PA 6444, PHB-71, KRH-2	2,876	850−2,215
Karnataka	KRH-2, DRRH-3	1,903	700−1,650
Maharashtra	Sahyadri, KRH-2, PHB-71, PA 6444	1,485	1,450−2,610
Andhra Pradesh	PHB-71, PA 6444, DRRH-1	600	650−1,170
Tamil Nadu	CORH-2, CORH-3, ADTRH-1, PHB-71, DRRH-3	1,069	715−1,210
West Bengal	PA 6444, PHB-71, KRH-2, CNRH-3	710	1,020−1,670
Odisha	PA 6444, PHB-71, KRH-2	858	810−1,050
Uttaranchal	PSD-1, PSD-3, PHB-71	640	780−1,158
Goa	KRH-2, Sahyadri	680	780−1,155
Bihar Chhattisgarh Jharkhand	KRH-2, PHB-71, PA 6444, Sahyadri, DRRH-1, PSD-3	1180	950−1,870
Punjab			
Haryana Gujarat, Tripura			
	Total	12,001	

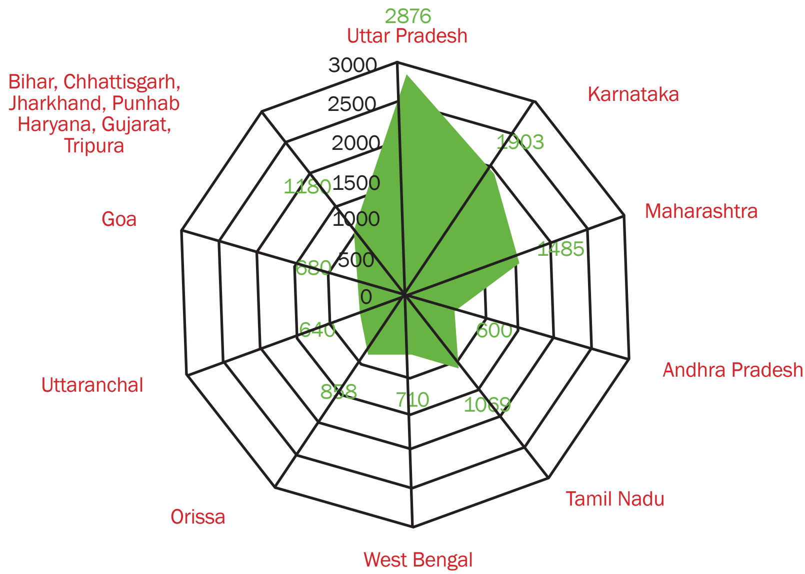

Fig. 2. FLDs on hybrid rice by state.

The skewed distribution in terms of the number of FLDs conducted in Uttar Pradesh, Tamil Nadu, Maharashtra, Karnataka, and Andhra Pradesh is due to the release of first-generation hybrids in these states and more emphasis given during the UNDP project period. The number of FLDs sponsored during that period was more than in the later period.

Figure 3 indicates clustering in terms of the cafeteria of hybrids demonstrated. Farmers always need a cafeteria of hybrids that are suitable to their area. “One size fits all” may not work all the time. Within a state, there may be differential perceptions as far as the selection of hybrids is concerned. In such cases, it is better to plan demonstrations across the state with more hybrids. It can be noted here that more than three hybrids were demonstrated in each state, with at least one private-sector hybrid. This is a good approach, particularly when there is a limitation of funding.

Figure 4 shows the range of yield advantages with mean minimum yield advantage and mean maximum yield advantage recorded by hybrids in different states. The numbers represent the kg yield advantage of hybrids for every hectare in a particular state. It can be noted that a hybrid with the highest percentage of yield advantage may not necessarily be a hybrid that has wider adaptability within a state. In such cases, the percentage of yield advantage may help in enhancing farm-level productivity. A hybrid with an average percentage of yield advantage may have wider adaptability, which may result in enhancing production in a larger area. Hence, development departments may consider these hybrids for popularization programs in much larger areas. For further details on individual technologies and the farmers selected for the FLDs, the corresponding nodal officers (see www.fld.rkmp.co.in) in the state can be contacted.

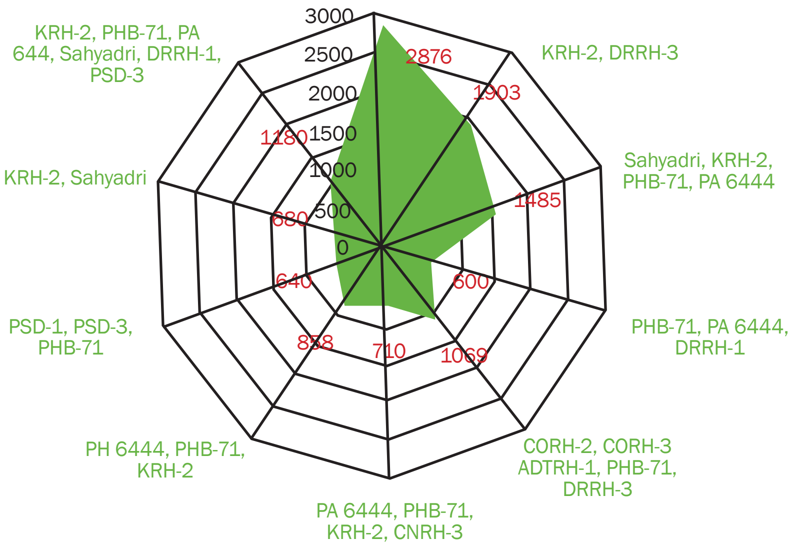

Fig. 3. Cluster of FLDs in cafeteria approach.

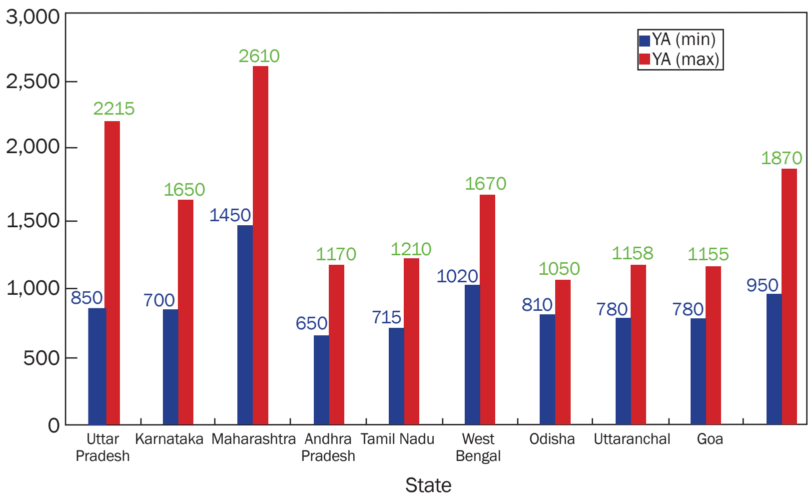

Fig. 4. Yield advantage range for hybrid rice.

Based on the yield advantages and perceptions of farmers and extension workers, over the years, some hybrids were found to be promising. The same was communicated to the Department of Agriculture (the public-sector extension department in India) for scaling up activities. State-wise promising hybrids identified over the years appear in Table 2. For Uttar Pradesh and Jharkhand, several hybrids were identified as promising. A recently released hybrid (DRRH-3) that has better grain quality (on a par with that of Samba Mahsuri, the most preferred variety in southern India) has

Table 2. Promising hybrids identified from FLDs by state.

State	2007	2008	2009	2010	2011
Gujarat	Indira Sona				DRRH 3
Jharkhand	PA 6444	PA 6444		PA 6444	PA 6444
	KRH-2	PHB 71		PA 6444 (SRI Method)	
		PUSA RH 10			
Karnataka	KRH-2	KRH-2			DRRH 3
Tamil Nadu	CORH-3	CORH 3		CORH 3	CORH 3
					DRRH 1
Uttar Pradesh	NDRH-2	PHB 71	PA 6444	PHB 71	PA 6444
	PHB-71	PA 6444			PHB 71
					DRRH 3
Chhattisgarh			Indira Sona		Indira Sona
Madhya Pradesh					PA 6201
Maharashtra	Sahyadri-4				
Uttaranchal	Pusa RH-10				
Pondicherry	CORH-3				

received good feedback in southern Indian states. States such as Chhattisgarh have established that a single hybrid (Indira Sona) can also be the most promising.

Year-wise and state-wise details of FLDs

To further explore the specific performance of a hybrid in a particular state, year-wise details are provided in Tables 3, 4, 5, 6, and 7. It can be observed from the data that the absolute yield of a hybrid may vary from state to state and year to year. But, it is important to see the comparative yields of hybrids in relation to the most popular HYVs in farmers' fields. Keeping in view the benchmark yields, hybrids were found to be higher yielding than HYVs.

The FLD program can generate awareness among the millions of rice farmers. But it is not possible to cover all rice farmers through this program alone. This should be supported by various other activities such as growth in the seed industry. The success of hybrid rice technology primarily depends on genetic purity, timely availability, and the affordability of hybrid seed to farmers. The production of pure hybrid seed at an affordable price in rice—a self-pollinated crop—is a highly skill-oriented activity. A good hybrid may not reach a large number of farmers unless it is feasible to commercially produce the seed on a large scale economically. Hybrid seed production technology is quite different from the technology for varietal seed production. Fresh hybrid seed is essentially purchased/procured by farmers every year/season. The hybrid seed should have purity of about 99%.

Table 3. FLDs on hybrid rice, 2011-12.

State	Hybrid	Area (ha)	Local check	Mean FLD yield (t/ha)	Mean check yield (t/ha)	% Mean yield advantage
Chhattisgarh	Indira Sona	17	MTU 1010, Mahamaya Local	4.51	3.62	24.5
Gujarat	DRRH-3	1	GR-11, Gurjari	5.16	4.30	20.2
Jharkhand	PA 6444	20	Local	6.27	3.33	88.2
Karnataka	DRRH-3	1	BPT-5204	6.80	6.69	1.6
	DRRH3	1	KRH 2	5.95	−7.30	
Uttar Pradesh	PA 6444	1	NDR 359	6.10	4.80	27.1
	PHB 71	4	NDR 359	6.00	4.80	25.0
	DRRH-3	1	NDR 359	4.90	4.20	16.6

Table 4. FLDs on hybrid rice 2010-11.

State	Hybrid	Area (ha)	Local check	Mean FLD yield (t/ha)	Mean check yield (t/ha)	% Mean yield advantage
Jharkhand	DRRH-2	6	Swarna	3.18	2.18	45.9
	PA 6444	14	IR64	6.01	3.55	69.3
	PA 6444	6	Swarna	7.02	5.45	28.8
	SRI Method		Normal Method			
Tamil Nadu	CO R H 3	2	Local check	8.28	6.68	24.0
Uttar Pradesh	PHB 71	15	Local Check	5.90	3.50	68.6

Table 5. FLDs on hybrid rice, 2009-10.

State	Hybrid	Area (ha)	Local check	Mean FLD yield (t/ha)	Mean check yield (t/ha)	% Mean yield advantage
Chhattisgarh	Indira Sona	10	HYV	6.75	3.25	107.7
Jharkhand	PA 6444	20	HYV			
Tamil Nadu	CO R H 3	16	HYV	6.96	5.06	27.5
Uttar Pradesh	PHB 71	18	Sarjoo	6.15	4.00	53.8

To link the state-wise market share with that of the FLD program, an attempt is made to provide details in Figure 5. A total of 17,355,000 tons of quality seed were made available in 2008 (Singh et al 2010). Growth of the seed market in the hybrid rice sector is a positive sign.

Table 6. FLDs on hybrid rice, 2008-09.

State	Hybrid	Area (ha)	Local check	Mean FLD yield (t/ha)	Mean check yield (t/ha)	% Mean yield advantage
Jharkhand	PA-6444, PHB-71, Pusa RH-10	125	HYV	5.45	3.6	51.4
Tamil Nadu	CO R H 3	40	HYVs	7.30	5.6	30.4
Uttar Pradesh	PHB 71	8	Local Check	6.75	4.0	68.8

TTable 7. FLDs on hybrid rice, 2007-08.

State	Hybrid	Area (ha)	Mean FLD yield (t/ha)	Mean check yield (t/ha)	% Mean yield advantage
Chhattisgarh	Indira Sona	10	3.92	3.44	13.9
Jharkhand	PA-6444,	163	6.10	3.67	66.2
	KRH-2	137	4.78	3.67	30.2
Karnataka	KRH-2	50	7.90	6.90	14.5
Puducherry	CORH 3	5	5.09	3.96	28.5
Uttar Pradesh	PHB 71	10	7.80	5.87	32.9
	NDRH-2	12.8	6.33	4.77	32.7
	DRRH-3	1	4.90	4.20	16.6

Yield gap analysis in the perspective of FLDs

Figures 6 and7 give glimpses of yield gap analysis for 2011 and 2007, respectively. Two types of yield gaps are calculated: Yield Gap 1 and Yield Gap 2. Yield Gap 1 is the difference in yield obtained on the research station's farm and the potential or possible yield obtainable in farmers' fields. This yield gap is due to nontransferable technologies, the environmental difference between the research station farm and farmers' fields, etc. Yield Gap 2 is the difference in potential obtainable yield in farmers' fields and the actual yield obtained by farmers. This yield gap is bridgeable. In fact, through frontline demonstrations implementing the entire package developed in a holistic way, the potential obtainable yield in farmers' fields can be demonstrated to neighboring farmers. The actual causes for Yield Gap 2 may be many, which can be broadly classified as biological constraints and socioeconomic constraints.

In the present context, yield gap analysis gives an excellent opportunity for scaling up strategies. For example, Yield Gap 2 in Chhattisgarh was 24.5%, which means there is a potential for increasing production to this tune, if Indira Sona is adopted by farmers across the state. This gap is due to the difference in yields obtained between Indira Sona and locally adopted HYVs. Similarly, Yield Gap 1 in the same state was 50%. This was obtained by calculating the difference between the yield obtained from Indira Sona at the research station and in FLD fields. Large-scale adoption of Indira Sona may lead to bridging the yield gap to the range represented in Figure 6.

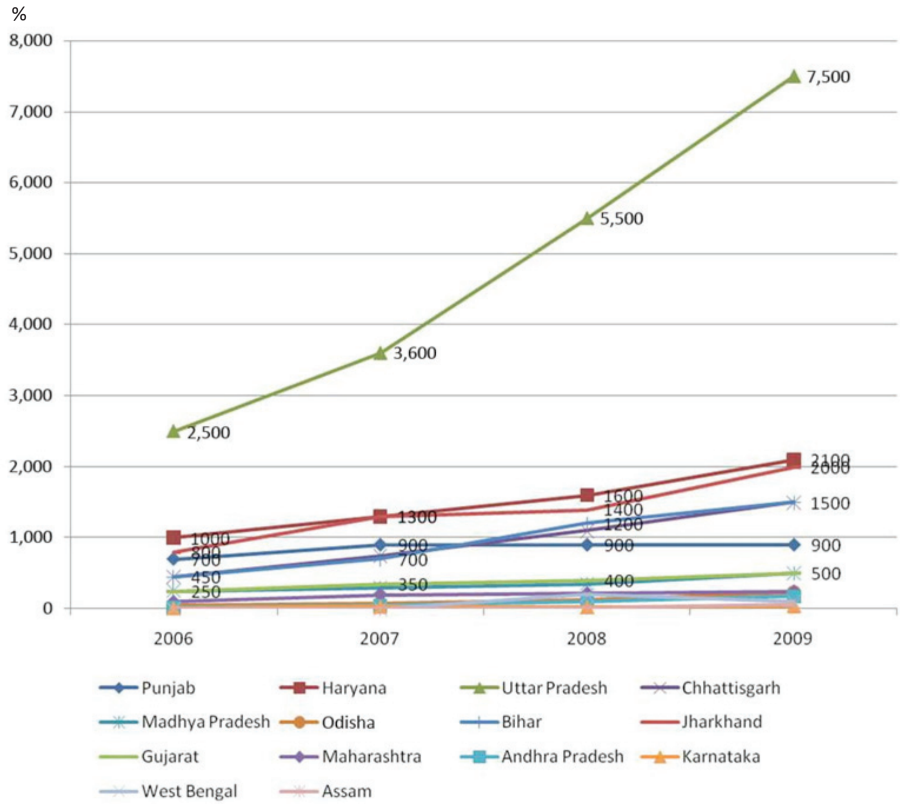

Fig. 5. Linking FLDs to market size.
Source: Singh AK (2010).

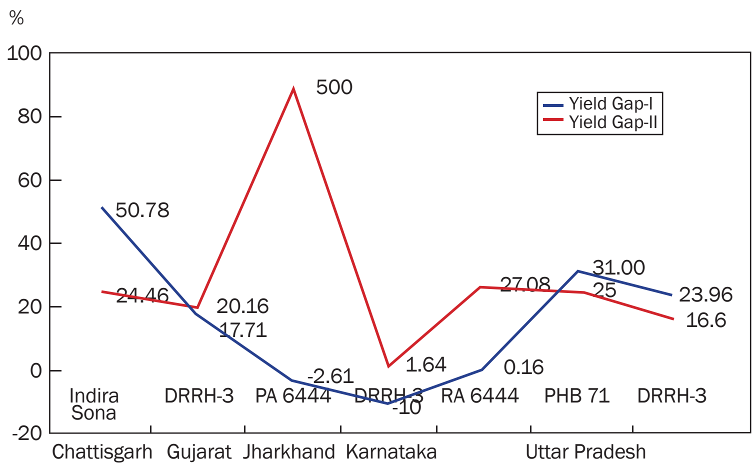

Fig. 6. Yield gap analysis, 2011.

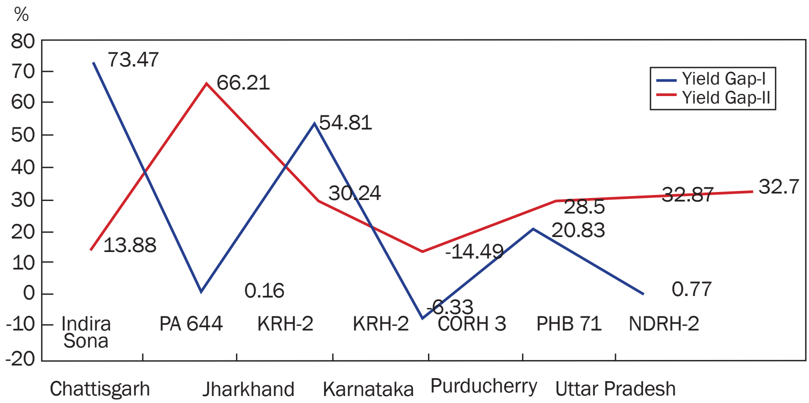

Fig. 7. Yield gap analysis, 2007.

Moving beyond yield advantages: earlier experiences of FLDs

Various studies have documented hybrid rice adoption by farmers for the past decade. Some of them concentrated on the socioeconomic dimensions of hybrid rice adoption and some focused on a comparative analysis of the profitability of hybrid rice adoption with that of high-yielding varieties. Very few studies have focused on the institutional efforts required for large-scale adoption of hybrid rice in India. Here, we attempt to analyze farmers' experiences with hybrid rice in general and FLDs for hybrids in particular.

Most of the FLD farmers believed that the amount of fertilizer required and weed incidence were the same in the case of hybrids compared with inbreds. Although some FLD farmers believed that crop management skills varied, a majority felt that it was more or less the same. About two-thirds of the hybrid rice farmers expressed marketing problems as the most prominent constraint to large-scale adoption. In the case of hybrid seed production, average yield was around 2 t/ha, which many farmers perceived as satisfactory. Hybrid seed was procured by the agencies with whom farmers had contracts. In Andhra Pradesh, the price paid for procurement of seed ranged between Rs.[1] 22 and Rs. 26 per kg. On average, the net returns from seed production over variable cost were Rs. 35,185 per ha during 2002. Farmers opined that seed production required considerably more laborers, especially for rope pulling, roguing, leaf clipping, etc., which led to increased demand for labor. Seed production in Mandya and Mysore districts of Karnataka yielded high net returns of around Rs. 70,000 per ha. For Uttar Pradesh and Uttarakhand, more than 85% of the farmers stated that they were satisfied with hybrid rice cultivation for its yield and profitability. A large number of farmers believed that the hybrids could be grown in both upland irrigated and shallow lowland conditions irrespective of the size of holdings. The net

[1] Rs. indicates Indian rupees (US$1 was equivalent to 40 Indian rupees at the time of this study).

profit received from hybrids was Rs. 14,894 per ha compared with Rs. 11,131 per ha obtained by cultivating inbreds. The cost of cultivation for hybrids was estimated to be Rs. 16,409 per ha.

Perceptions of farmers and extension workers

Some 70% to 80% of the farmers and extension workers were convinced of the hybrid rice yield advantage over inbred rice. They were in agreement that the pace of area expansion of hybrid rice may be restricted to some extent because of the need for seed replacement every year. A majority of the respondents did not agree about the notion of poor grain filling of hybrid rice and also higher chaffiness. Some 72% to 83% of the respondents considered hybrid rice more profitable than inbred rice. A majority of the hybrid rice growers did not agree with the higher grain breakage of hybrid rice. However, in their opinion, hybrid PA-6201 has some breakage if shelling is done without parboiling of the seed.

Perceptions of millers

The perceptions of millers toward hybrid rice are given here for a comprehensive understanding of hybrid rice adoption in northern Indian states. More than 53% of the millers stated that the hulling percentage of hybrid rice is lower than that of inbred rice. Millers with larger plants and the department of civil supplies did not offer a lower price for hybrid rice. However, owners of hullers and small rice mills purchasing small quantities have artificially created the opinion of higher breakage and they were offering a low price for hybrid rice.

Issues emerging out of earlier FLD experiences

One of the major issues that emerged very clearly out of the FLDs organized during the first decade of FLDs was that hybrids have a clear and significant yield advantage over high-yielding inbred varieties in most cases. This yield advantage was found to be very high in Jharkhand, Chhattisgarh, and Uttar Pradesh, wherever benchmark yields were low. The yield advantages in Punjab, Haryana, Andhra Pradesh, and Tamil Nadu were found to be lesser, as these states already have very high productivity through the cultivation of high-yielding improved inbred varieties coupled with the latest management practices. Inconsistency of the yield advantage of hybrids could be traced to either inadequate or defective management practices adopted. Sometimes, this inconsistency was also due to the poor quality of hybrid seed used.

The second major issue was the lesser price offered by traders and millers for the produce of hybrid rice, particularly in southern states such as Tamil Nadu, Karnataka, and Andhra Pradesh. The price offered was Rs. 40–80 less than for varieties with similar grain type (way back in 2002). But, slowly, this issue is being resolved by a majority of the states. The way out is to sensitize traders/millers about the advantages of cultivating hybrid rice and about the comparative profile of grain quality of inbred varieties and hybrids. In the recent past, hybrids with better and requisite grain quality characteristics for southern India have been developed and released. This should solve the adoption problems in southern India.

The third major problem for the large-scale adoption of hybrid rice as expressed by many FLD farmers was the higher seed cost. At present, hybrid seed cost ranges from Rs. 80–120 from public-sector seed agencies to Rs.120–200 from private-sector seed companies. Though the recommended seed rate is 15 kg/ha, farmers in Punjab, Haryana, and western Uttar Pradesh are adopting 10–12 kg/ha. Public-sector seed agencies are producing less than 3% of the total hybrid rice seed produced in the country. Almost all the hybrid seed in the country is produced and marketed by the private sector. The price of seed is fixed by private-sector seed companies based on various factors in a free and market economy. It is not possible to ask the private sector to reduce the seed price; instead, by creating more competition in the market, prices can be reduced or stabilized. Since the price of the seed produced by the private sector cannot be reduced, the other practical alternative is to reduce the seed rate per hectare. Fortunately, the seed rate is very low, 5 kg/ha under the System of Rice Intensification (SRI) that was being popularized during the same period.

The fourth major issue that emerged out of the organization of these FLDs was that there is no significant difference in pest and disease incidence between hybrids and high-yielding inbred varieties if preventive measures are taken by regular periodic spraying, as is the norm. Though there is no specific resistance to/tolerance of major pests and diseases in hybrids, if the crop is managed properly, the incidence of diseases and pests is not a major problem in the cultivation of hybrids. However, hybrids with specific resistance to/tolerance of some of the major pests and diseases are under development now and may become available for general cultivation during the next 5 years.

Future prospects of FLDs on hybrid rice

Efforts should be made to increase the multiplier effect of frontline demonstrations. Once FLDs are conducted, follow-up activities should take place so that the large-scale adoption of demonstrated varieties/hybrids/technologies is realized. To have a visible impact, it should be assured that a complete package of practices is adopted in demonstration plots. In the absence of a complete package, the potential yield of demonstrated technology will not be perceived by farmers. Wherever possible, farmers' innovations can be included along with the demonstrated package of practices. There is a need for a paradigm shift in the FLD program. The funding-centric approach needs to be replaced by a need-centric approach. The yield advantage perspective should be replaced by "problem-solving" capability of new technologies. There should be continuous demonstration fora (which result in regular dialogue between FLD farmers and neighboring farmers) in place of a single field day. This will also promote continuous learning opportunities among farmers.

Process documentation is one area that needs to be carried out immediately for the scaling up of successful technologies. Along with success stories, cases of failure should be reported. Impact assessment methodologies for the FLD program should be redefined. This should not focus only on yield advantages but should also focus on the number of farmers adopting a demonstrated technology after a few seasons. There is a need to integrate the concept of yield gaps into the FLD program. For this, existing yield gaps at the local/district level should be determined and FLDs should address those yield gaps. Time-series data of FLD technologies should be made available. Integrating an ICT approach in FLDs will help maximize the impact of technologies markedly. Integration should be in the form of documenting the various activities undertaken in demonstration plots such as method demonstrations, field days, etc.

Developing a strategy for FLDs on hybrid rice

To further enhance the effectiveness of FLDs on hybrid rice, there is a need to develop a sound strategy beyond the traditional way of conducting demonstrations. Such a strategy should answer the following six broad questions.

1. Will mere yield advantages lead to large-scale adoption?

FLDs traditionally focus more on the yield advantages of hybrids over existing HYVs. Mere yield advantages will not lead to acceptance and adoption among rice farmers. Examining the issue of profitability should be the aim of FLDs rather than simple yield advantages. Profitability at the farmer level may be due to higher yields, higher market price, reduced cost of cultivation, etc. The relative advantages of hybrids in terms of simplicity of package of practices, compatible practices, and predictable and consistent yields over seasons may be good indicators for success.

Similarly, these micro-level productivity issues should be reflected in macro-level production strategies and policy guidelines. In the absence of this, critical services will not be available to those farmers who have interest in adopting hybrid rice.

An institutional mechanism? The positive consequences that emerge out of hybrid rice adoption need to be harnessed for further popularizing hybrid rice. The need for hybrid rice adoption should be seen in the view of alternate scenarios of food security in the absence of hybrids. "What would be the level of food insecurity in the future in the absence of hybrid rice adoption?" should be assessed through scenario projections. Institutional readiness to make certain structural and functional adjustments to derive benefits out of hybrids needs to be carried out. Further, adoption of hybrid rice on a large scale would lead to crop diversification in some areas. That's a kind of indirect advantage in rice-based farming systems. The intensive labor requirement (30% more, or 300 person-days per hectare) would lead to the creation of rural employment to a limited extent. As in the case of the Hybrid Rice Commercialization Program (HRCP) of the Philippines and other countries, notable policy interventions such as a seed growers' subsidy, seed distribution, seed pricing and procurement, and hybrid rice pricing and procurement could be taken up by public institutes.

2. Will single-plot demonstrations lead to conviction?

Single-plot demonstrations may not lead to farmers' conviction about hybrid rice. A cluster approach seems to be more appropriate. FLDs can be planned for a cluster of 10 hectares involving several farmers' fields. This enables farmers to become convinced about the advantages of adopting hybrid rice. These clusters can be identified based on need at the village, block, and district levels in each state. The cluster approach should be linked to demonstrations of the private sector in that area.

As was mentioned earlier, there is no point in demonstrating a single hybrid in farmers' fields in a given area. A cafeteria of hybrids suitable to an area can be demonstrated, so that farmers can choose among the available hybrids.

3. Are scaling-up options adequate?

Once demonstrations are conducted, there are no adequate follow-up activities. The strategy should involve a large number of stakeholders who would be responsible for scaling-up activities. The strategy of FLDs accordingly should have pre-scaling-up activities, impact indicators, and capacity building. For a scaling-up strategy, the first step is to identify the ecosystems. Irrigation was considered as a crucial input for hybrid rice cultivation. But, in many countries, including India, hybrids gave better results in unfavorable soil and climatic conditions than in favorable irrigated rice ecosystems. Hence, a proper analysis needs to be made in the country. Second, is the purpose of rice farming commercial or subsistence?

4. Hold prescriptive or participatory demonstrations?

The futuristic aim has to be on increasing the impact of appropriate high-potential hybrid rice interventions, and promoting their adoption through the development and application of improved dissemination strategies. Public- and private-sector partnerships along with active involvement of farmers may adapt the resource-test-demonstrate-adopt model for the large-scale adoption of hybrids. When there are appropriate roles and decision-making processes, this may be the most effective, broad-based, and sustainable solution. Partnerships among NGOs and private and public organizations are likely to be the agents of change for the future, although the most appropriate combination for a given situation will vary depending on the existing circumstances and technology. It is expected that in the near future a network of partnerships with participatory hybrid selection will enable hybrid rice pull by farmers.

5. How do you make learning effective using ICT?

Nationally, there is a need to develop an online platform for providing a complete database of frontline demonstrations. This platform should facilitate real-time (online also) data sharing. The success stories of FLD technologies should be placed online for use by state departments of agriculture. Integrating the information and communication technology (ICT) approach in FLDs will help in maximizing the impact of technologies markedly. Integration should be in the form of documenting the various activities undertaken in the demonstration plots such as field days, etc.

6. Is strategic planning effective?

A strategic planning document exclusively for popularizing hybrid rice through FLDs could be developed. For example, the Indian government is planning to launch a program called "Farmers First" involving a large number of demonstrations. Such demonstrations can be integrated with the hybrid rice popularizing activities. A target of expanding hybrid rice area to 5 million hectares could be possible in 5 years' time with 10,000 FLDs each year (50,000 FLDs in 5 years) and with substantial supporting services.

Conclusions

Hybrid rice development, large-scale seed production, extension efforts, and institutional support should go hand in hand in order to achieve the coordination required to popularize hybrid rice in India. Front-line demonstrations have tremendous potential to generate awareness and interest among farmers, thereby stimulating the large-scale adoption of hybrid rice across the country. Regular evaluation studies and feedback emanating from FLDs should continue to help hybrid researchers to evolve better hybrids that are location-specific, thereby creating a demand-driven environment. The continued efforts on the part of hybrid generators, technology transfer specialists, and social scientists will bring about a paradigm shift in the near future, whereby the "hybrid rice pull" by rice farmers will dominate the "hybrid rice push" by development practitioners. Increased rice productivity and production contributed by the large-scale adoption of hybrid rice will undoubtedly form a major component of national food security in the decades ahead.

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Notes

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Challenges in hybrid rice seed production from the private sector's perspective

Ish Kumar, Rupendra Singh, T. Jaya Prakash, and Sukhpal Singh

Systematic research efforts for hybrid rice development began in India in 1989 and soon after that many rice hybrids were developed by both the public and private sector in India. Although many rice hybrids have been officially released, only a very few hybrids have gained market significance. After growers realized that these rice hybrids significantly outyielded the popular high-yielding rice varieties, hybrid rice seed production is now gaining significance as an agricultural industry. Although rice varietal seed production is primarily with the public sector, approximately 95% of hybrid rice seed production is with the private seed industry.

The lack of availability of suitable hybrids and the high cost of hybrid seed are two of the major constraints in the low adoption of rice hybrids. The cost is primarily attributed to the low hybrid seed yield, which varies from 0.5 to 4.5 t/ha, with an average of 1–1.5 t/ha. It is expected that, with the availability of improved high-yielding rice hybrids having biotic stress resistance and high milling and cooking quality features, the demand for hybrid rice seed could swell to 8–10 million hectares, requiring 120,000–150,000 tons of hybrid rice seed each year. It is estimated that currently about 25% of the likely future demand for seed is produced by various private seed companies in India.

In this chapter, the current challenges facing the private sector, availability of CMS lines with high pollination, genetic purity of female line seed, synchronizating of the hybrid parent flowering, isolation from undesirable varieties, limited identified areas for seed production, differential response of parental lines to weather risks (such as drought, high temperatures, hot winds, and hail), trained labor availability, the technical knowledge base required of specialized seed producers, issues regarding seed certification and marketing of private-sector hybrids, subsidies, seed procurement dynamics, freight costs, and other economic, management, business, and ethical factors have been studied for developing the hybrid rice market such as that in India.

The ever-increasing need to enhance productivity per unit area in rice is gaining more and more significance, due to both increasing population pressure and decreasing land area. In the recent past, low genetic gains in yield in developing new rice varieties have been experienced. Out of various genetic approaches adopted to raise the genetic yield ceiling, hybrid rice technology proved to be one of the most potent ones. Successful rice hybrids are known to yield 15% to 20% more yield than improved high-yielding varieties with the same growth duration.

To develop commercial three-line rice hybrids, and female lines with cytoplasmic genetic male sterility, male lines with high restoration ability and hybrids with higher heterosis are prerequisites. Male sterility through the cytoplasmic genetic male sterility system makes the pollen of female lines sterile and thus unviable. Such a male sterile line, when grown side by side with a pollen parent in an isolated plot, produces hybrid seed due to out-pollination from the adjoining male fertile restorer parent. Hybrid seed, set on CMS plants, is used for growing a commercial hybrid crop. Hybrid seed productivity, however, depends on various genetic and nongenetic factors.

Systematic efforts to develop and use hybrid rice technology in India began in 1989. With concerted research work, India developed and officially commercialized more than 40 rice hybrids. Because of various factors, only a very few hybrids have gained a significant market share. It was indeed after such superior rice hybrids became available that remarkable growth in private-sector investment was witnessed. The hybrid rice seed industry now has a well-established base in India. After China, India is the only country with benchmarks of producing more than 44,000 tons of hybrid rice seed (Fig. 1). Although the yield in hybrid rice seed production in many cases is known to be 1.5–1.8 t/ha, the general trend appears in Figure 2.

Examples have also been reported with hybrid seed yield from 4.5 to 6.5 t/ha (Figs. 3 and 4).

However, the private-sector hybrid rice seed industry still faces certain challenges in hybrid rice development and its seed production (availability of desirable CMS lines, low hybrid seed yield, the high cost of hybrid rice seed, the varying requirement of cooking and eating quality in different regions, etc.) and these are discussed below.

Genetic challenges

CMS lines with high out-pollination

High out-pollinating CMS lines are the backbone of a hybrid rice program in the private sector. Until recently, CMS lines primarily developed by IRRI were used in developing commercial hybrids. Except for one or two CMS lines, other female lines developed by IRRI or locally by seed companies have shown average to low out-pollination in commercial seed production programs. In the recent past, a few private companies (multinational and local companies) have developed new CMS lines with desired duration, desired grain type, and high stigma exsertion. These new CMS lines have shown very high out-pollination potential (3.5–6.5 t/ha) but most of the hybrids so developed with these lines grew tall and were prone to lodging, though a few dwarf hybrids were also developed. In the recent past, no new high out-pollinating CMS lines have been released to the private sector by the public sector or IRRI for com-

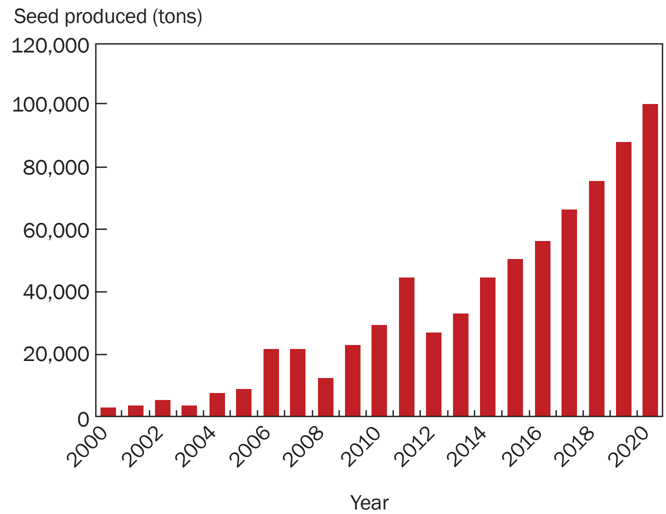

Fig. 1. Estimated hybrid rice seed production in India (tons).

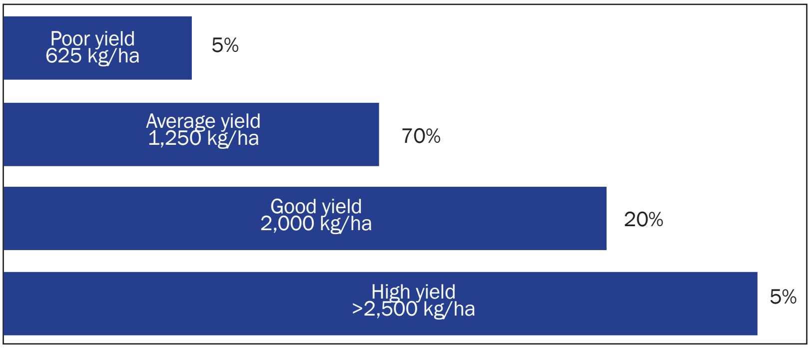

Fig. 2. Trends in hybrid seed production in farmers' fields.

mercial use in India or in other countries outside China. The major constraint of the high cost of hybrid seed could be overcome through these limited CMS lines. Much more effort is needed in breeding new CMS lines with high outcrossing potential in different grain types and duration. The private sector has developed some collaboration with IRRI and local partners to develop such lines.

Low stigma receptivity

The stigma receptivity of CMS lines at the flowering stage, when the male anthers are ready to dehisce pollen, is a crucial factor for the success or failure of hybrid seed set. The receptive stigmas are known to have high enzymatic activity and the presence of several enzymes at this stage allows pollen grains to germinate and fertilize the egg cell to produce hybrid seed.

Fig. 3. Picture showing yield of 6.5 t/ha in a hybrid seed production plot.

Fig. 4. Picture showing yield of 6.5 t/ha in a hybrid seed production plot.

In its experience, the private sector has observed differential behavior of some recently bred CMS lines with highly exserted stigmas with environmental factors at flowering. One CMS line with highly exserted stigmas was observed to have very poor seed set in the rabi (dry) season compared with other female lines with highly exserted stigmas. Though this female line had very heterotic hybrids, because of low stigma viability, seed set was low. This resulted in a very high cost of goods produced. The development and availability of any rapid tests/molecular markers for the development of CMS lines with relatively less sensitivity of the stigma at higher flowering temperature (37-41 °C) are a challenge.

Since the spikelets of male and female parental lines flower at different dates or bloom at different times, the information on timing and duration of stigma receptivity for a specific female line should be known before it is used in seed production on a large scale. However, this information is not currently available to hybrid seed producers for outsourced hybrids. Such information would help seed producers to select favorable/conducive areas for the seed production of each hybrid.

Concerns regarding pollen dehiscence

Another important factor for high hybrid rice seed production is the synchrony of anther dehiscence of restorer lines when the CMS parent spikelets are ready for outcrossing. At the time of anthesis, the pollen grains are known to swell rapidly in response to the floret opening and this causes the theca to bulge, thus rupturing the septum that will release the pollen. In our experimental hybrid seed production experience, we have observed many restorer lines that showed low or no anther rupture with force in the dry season due to inadequate anther swelling. Hybrid rice seed production with such restorer lines has been observed to be very poor and such pollen parents need to be identified in the early stages. Finding molecular markers for such a characteristic is a challenge. Sharing of such information on such parental lines with hybrid seed producers would help them to identify suitable areas for seed production of such hybrids.

Susceptibility to pests and diseases

The parental lines for most current hybrids are susceptible to biotic stresses, thus affecting their potential in hybrid seed production fields. The development of stable CMS lines with resistance to brown planthopper (BPH) and bacterial leaf blight (BLB) is a big challenge. Some success has been achieved in breeding A and R lines for BLB but BPH-resistant parental lines are still a challenge.

Climate-related challenges

The flowering synchrony of A and R lines is another very important factor in hybrid seed production. In the already produced hybrids, there are not many issues in managing the synchrony of both parental lines. But, failure of flowering synchrony of male and female parents is a common feature in the new hybrids or at the new locations because of a lack of reliable flowering data or inexperienced farmers for hybrid seed production. Frequent climatic variations also cause some problem in predicting synchrony and many times companies may have to compensate farmers for lower yields.

There is still a challenge of managing and perfecting the synchrony of parental lines through the use of hormones and chemicals.

Social and political challenges

Organizing consolidated seed production areas

It is expected that, with the availability of improved high-yielding rice hybrids with biotic stress resistance, and high milling and cooking quality, the demand for hybrid rice seed may swell to 8–10 million hectares, thus requiring 120,000–150,000 tons of hybrid rice seed each year. To produce a large quantity of hybrid seed, the success of the private sector will depend on the consolidation of hybrid seed production areas. Area consolidation helps the companies to assure isolation of seed production plots for better quality control, easy monitoring from time to time, and making logistics and transport arrangements as and when required. Consolidation thus results in better control of the cost of goods produced.

On account of farmers' experience in hybrid seed production in many crops and rice cultivation experience in the dry season, the farmers in a few districts of Andhra Pradesh undertook hybrid rice seed production. Currently, nearly 90% of the hybrid seed is produced in this limited geography in Andhra Pradesh. Due to small landholdings, nearly 3,000 villages and >40,000 seed growers are now involved in hybrid seed production and managing such a large number of personnel and locations is a challenge in itself. On account of the increasing hybrid rice seed demand, organizing the required consolidated area (seed village concept) with already experienced farmers is a challenge. Moreover, training the supervisory staff on the one hand and training the new farmers on the other with the latest seed production technology is also a big challenge facing each company in the private sector.

Hybrid rice seed procurement price fixation

In order to capture large-scale seed production areas and to ensure profitability to farmers, seed production companies have to guarantee a minimum hybrid seed yield and seed procurement price before undertaking the activity. The big challenge facing the companies is to ensure high hybrid seed yield and purity. More efforts are thus required from the company side to ensure timely steps by farmers to increase seed yield and monitor the crop throughout its life cycle for purity.

Another challenge sometimes faced during fluctuations in hybrid seed yield is the cross-purchase of seed from farmers that obtain high yield, which creates difficulty in compensating the marginal and low-yielding farmers. Sometimes, a sudden increase in the commercial grain price, before harvesting the hybrid seed production plots, affects the already agreed-upon hybrid seed procurement price. There is a challenge to maintain seed production areas under those hybrids that offer less profitability to seed production farmers.

No system to forecast the hybrid seed requirement

Another big challenge facing the companies is to forecast the seed requirement for the coming seasons. Companies use their own market intelligence to forecast or create hybrid seed demand based on hybrid performance. But, presently, there is no mechanism to know the hybrid rice seed demand from the public sector for subsidy programs in advance. This results in variation in supply and demand of the most demanded seed.

Hybrid seed production of public-sector licensed hybrids

For the seed production of rice hybrids licensed from the public sector, a compulsion to buy breeder seed every year from the public sector posed certain challenges to the private sector. A big challenge faced by the private sector for these public-sector hybrids was that of the purity of the breeder seed and its timely availability. Certain impurities in the supplied breeder seed posed difficulties in the production of pure hybrid seed and this affected the compensation paid to farmers.

Timely labor availability

Hybrid rice seed production is indeed a very labor-intensive activity as it requires about 30% more labor than that of seed production in improved rice varieties. In hybrid rice seed production, timely planting of male and female lines (depending on their staggering period) is a must. Arranging for labor at transplanting and/or at flowering time for roguing or supplementary pollination is another challenge. Because of many government schemes and greater urbanization activities, a labor shortage now occurs in the seed sector. The challenge facing seed production agencies is to mechanize most of the operations to timely handle a large seed production area.

The short seed-processing window

Most hybrid rice seed production is undertaken in southern India in the dry season, so the sudden arrival of raw seed raises seed storage, processing, and handling problems. The companies have a challenge to arrange or build short-term seed storage facilities near seed production centers or seed-processing units. In the storage of freshly harvested hybrid seed, high moisture content results in reduced seed viability very fast. Moreover, because of small landholdings, many lots with a small quantity of seed are produced. The drying and processing of these small lots and their record keeping pose numerous challenges at the warehouse and processing centers.

Seed dormancy

Since more than 90% of the hybrid seed is produced in the dry season, it is harvested in the second fortnight of April to early May and is dried, processed, germination-tested, packed, and transported in early May to early June. Dormancy in freshly harvested seed delays germination test results and thus market placement of seed. There is a challenge to develop some reliable technique to break seed dormancy on a commercial scale. There is also a challenge for the seed industry to mechanically dry/sun-dry a large quantity of seed before seed processing without affecting its germination percentage.

Grow-out tests for ascertaining seed purity

The time between the arrival and dispatch of hybrid rice seed is very short. The seed indeed has to be dispatched to the market immediately after seed processing, quality assurance, and packing, etc. Ascertaining the genetic purity of different seed lots through grow-out tests (GOT) cannot be done because of the very short period before going to the market. Though utmost care is taken to ensure the purity of hybrid seed in the main seed production fields themselves, still the purity of some seed lots needs verification. There is a challenge to ascertain the purity of all such lots in the absence of the availability of any reliable molecular marker technique and to avoid time-consuming GOTs.

Seed inventory challenges

Management of seed inventory for timely processing, packaging, quality assurance, on-time supply to the market, handling of seed returns from the market, and rejections of seed with low germination are common challenges facing seed companies. All these activities affect the planning of seed production and profitability of the company. Safe storage of unsold leftover inventory involves high storage cost, for example, cold storage cost, etc., thus affecting COGS (cost of goods) and the next-year production plan, too.

Other problems and challenges

Sometimes, other problems such as restrictions of seed movement across geographies within and outside the seed-producing countries, the policy on support for seed production and intervention for additional payment to growers in case of poor yield due to any natural calamities, and minimum support price are present. Moreover, hybrid rice seed sale problems in various states affected seed production plans because of certain government decisions such as putting a sudden ban on hybrid rice seed sales or a lower hybrid rice grain sale price, which affected the adoption of rice hybrids. Similarly, seed certification of private-sector hybrids for participation in a subsidy program is another challenge.

It is realized that governments must make a clear road map to encourage the hybrid rice seed production sector through the creation of special hybrid rice seed production zones in the agronomically best geographies and make fundamental infrastructure such as water and electricity available in such zones.

Notes

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A tool to breed A lines with high outcrossing ability

J. Taillebois, J. Dossmann, and H. Paredes

In spite of higher yields, extension of hybrid rice is still strongly limited by the difficulties of producing seeds at a competitive price. In countries where mechanized sowing is common, such as those in Latin America where 100 to 200 kg/ha of seeds are currently used, the price of hybrid seeds is a big obstacle to broader hybrid rice diffusion.

Independently of being a three- or two-line system, hybrid rice seed production is based on outcrossing of a male sterile line by pollen of a male fertile line. The outcrossing ability of parental lines or seed production ability of hybrids is a key point for lower seed prices. To breed for outcrossing ability, it is necessary to have genetic variability and a tool to evaluate outcrossing ability on a large number of early-generation lines (F_2, F_3).

Through domestication, rice became a self-pollinated plant. The constant practice of pedigree selection for inbred breeding tends to continuously decrease the outcrossing ability of new lines. Inbred lines that are difficult to stabilize because they are more adapted to outcrossing are systematically rejected and consequently genes favorable for outcrossing are gradually lost. For this reason, the direct use of lines from an inbred breeding program to form hybrids is not the best way to get hybrids with good seed production ability.

The ancestors of rice are generally allogamous or partially allogamous and, probably, genes for outcrossing ability still exist but are dispersed within *Oryza sativa* germplasm. It was noted that inbred lines resulting from anther culture are more easily contaminated by outcrossing during seed production processes than lines from traditional pedigree selection (personal communication, G. Clement, Cirad). Contrary to inbreeding pedigree selection with anther culture, no selfing/stabilization is practiced to eliminate lines with positive gene associations for outcrossing ability. Since 2002, El Aceituno Company has based all its inbred selection strategy on recurrent selection. In this process, the best lines are, before fixing, recombined thanks to the presence of a male sterility gene. This recombination process favors most allogamous plants and thus maintains and concentrates on genes favorable for outcrossing within populations. It is now necessary to advance generations and speed up the fixation of lines to self-pollinate plants with paper or tissue bags. These observations seem to confirm that there are still outcrossing genes split across *O. sativa* germplasm and that controlled selection pressure could join these genes together and lead to more outcrossing-adapted lines.

To efficiently concentrate on an outcrossing-adapted gene through a selection process, it is necessary to evaluate outcrossing ability with precision on a large number of lines and as early as possible (S1, S2). The principle of testing outcrossing is based on the use of recessive genetic male sterility, the same sterility that is used in recurrent breeding programs throughout Latin America. This genetic male sterility, which comes from an induced mutation on IR36 (Singh and Ikehashi 1981), is perfectly stable and easy to identify at the flowering stage. Cirad recently developed marker-assisted selection that permits the identification of male sterile plant before flowering. Technology is now refined for identification at the seed level. The principle for evaluation of outcrossing ability with an ms gene is simple (Fig. 1). By selfing heterozygous (MS ms) plants, segregating lines for male sterility are obtained. The outcrossing of these lines is then evaluated by harvesting male sterile plants (ms ms) outcrossed by neighboring fertile plants (MS ms, MS MS). As fertile and sterile plants are from the same line, flowering synchronization is not a source of biased results. The mean yield of sterile plants is an estimation of line seed production ability, and the ratio of the mean yield of male sterile plants to the mean yield of fertile plants is an estimation of line outcrossing ability. The two evaluations are slightly different: a highly productive line can have a moderate outcrossing ability but good seed production ability and, reciprocally, a line with high outcrossing ability can have poor seed production ability because, as a fertile plant, it is poorly productive.

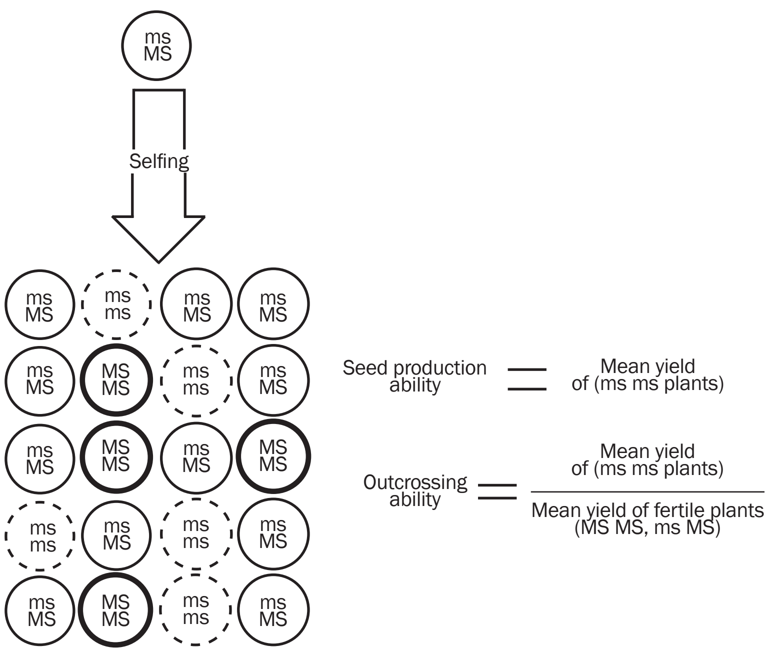

Fig. 1. Principle of an ms tool for evaluating outcrossing.

To verify the usefulness of this tool, we tested the outcrossing ability of 62 ms segregating F_3 lines. The F_3 lines were obtained from a cross between two inbred B lines, one male fertile (MS MS) and the other male sterile (ms ms). Because we are working with recurrent selection, we developed, for the most important B lines, sister lines segregating for the ms gene. F_1 plants (MS ms) were selfed and, among the F_2 population, fertile F_2 plants (MS MS, MS ms) were selected and selfed to produce F_3 lines. The F_3 lines were planted in a randomized complete block design with three replications. Plots were formed with four lines of five single transplanted plants (30 cm between plants). Male sterile plants were identified at the flowering stage. For each plot, male sterile plants were individually harvested and five fertile plants were harvested for the evaluation of outcrossing ability.

The flowering period of different lines was relatively narrow (10 days). Analysis of variance (Table 1) showed that there were very significant differences (P <0.0001) between outcrossing ability and outcross seed production ability of F_3 lines. The range of differences was very wide: from 2.2 g/plant to 26.8 g/plant for seed production ability and from 6% to 52% for outcrossing ability. With such a range of variability, selection for outcrossing ability is possible. If selection is possible, the conduction of evaluation trials is not easy, principally for Latin America, where transplanting is not common and labor is very scarce. If it is difficult to use this process routinely in a breeding program, the system can be useful for phenotyping outcrossing ability and finding molecular markers. Combining marker-assisted selection with ms and recurrent selection will speed up the process of breeding female lines with high outcrossing ability. Cirad and El Aceituno are now strongly involved in the identification of molecular markers linked to outcrossing ability.

In a hybrid breeding program based on recurrent selection, like those of El Aceituno/Cirad in Colombia or Embrapa/Cirad in Brazil, an ms gene is used for recombination but also as a tool to produce testcross seeds for the early testing of yield and grain quality combining ability. Testcross seeds are produced by crossing male sterile plants of tested lines with a tester. Tested lines are alternately transplanted with lines of the tester and, before flowering, fertile plants of tested lines are destroyed (marker identification can ease the process). Testcross seeds are harvested on male sterile plants outcrossed by the tester. The seeds are then used to test, in multilocation trials, the yield and grain quality combining ability of tested lines.

To verify whether it was possible to use the results of testcross seed production as a selection criterion for seed production ability of tested lines, we analyzed the results of a seed production testcross trial. One hundred and twenty-nine S1 lines were

Table 1. Analysis of seed production ability of F_3 lines.

	Degrees of freedom	Sum of squares	F value	P (>F)
Block	2	123	3.2	0.04*[a]
F_3 lines	61	4,380	3.7	0.00***
Residuals	122	2,344		

[a]* = significance at 5% level, *** = significance at 0.1% level.

crossed with four testers: three inbred lines and a population. For each combination, a mean of 10 male sterile plants was harvested and mean seed production of the tested lines was calculated for each tester/tested line combination.

The correlations between the results of different testers were all significant independently of which tester was used (Table 2). Analysis of variance (Table 3) showed very significant differences between the tested lines (*P* <0.0001) and, as for precedent analysis, the range of seed production ability was very wide, from 2.2 g/plant to 37.5 g/plant (Table 2). So, it is possible to use the results of testcross seed production to evaluate outcross seed production ability and combine testcrosses for yield and grain quality combining ability with seed production ability.

Using the results of testcross seed production as a selection criterion, we can restrict yield and grain quality testcross evaluations only to those lines with high seed production ability. Consequently, fewer resources will be needed to conduct a breeding program or, with the same resources, testcross yield evaluations could be conducted at more locations.

In a hybrid rice breeding program based on reciprocal recurrent selection, like those in Colombia with El Aceituno/Cirad and in Brazil with Embrapa/Cirad, two heterotic populations are progressively formed. One is used as a germplasm source to produce female lines and the other to produce pollinator lines. As basic selection on both populations is through ms-based tesscrosses, the integration of selection for outcrossing ability is easy: it is just necessary to note the number of ms plants harvested for each testcross. Nevertheless, if selection for outcrossing ability is direct for the female population, selection for pollination ability on the male population will be effective only if genes for pollination ability are linked with those for female outcrossing ability. If linkage is probable, no real proofs of such linkage are available, and a confirmation is needed to confirm that this selection technique can be used to select outcrossing ability of pollinating lines.

Table 2. Correlation between tester results of S1 line seed production testcrosses.[a]

	B5	B1	P4
B21	0.60***	0.61***	0.55***
	B5	0.59***	0.63***
		B1	0.73***

[a]*** = significance at 0.1% level.

Table 3. Analysis of S1 line seed production ability.

	Degrees of freedom	Sum of squares	F value	*P*[a] (>F)
Tester	3	8,190	6.1	0.00***
S1 lines	128	22,275	96.2	0.00***
Residuals	384	10,893		

[a]*** = significance at 0.1% level.

To breed new B lines by pedigree selection from the best S1 coming from the recurrent selection process, outcrossing ability can be used as a selection criterion without additional work, using only seed production testcrosses. That allows an important savings in resources because only testcrosses from lines with higher outcrossing ability need to be evaluated for yield and grain quality. Moreover, other resources are saved because only B lines with high outcrossing ability are converted into A lines.

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Notes

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Introgressions from *Oryza rufipogon* into restorer line KMR3 increase hybrid rice yield

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Oryza rufipogon is a good source of yield-enhancing genes/QTLs but introgression lines (ILs) have not been used in hybrid rice production. We earlier identified a yield-enhancing QTL (*yld2.1*) flanked by RM262 and RM263 from *O. rufipogon*. Twenty-seven high-yielding derivatives of restorer line KMR3 with homozygous introgressions from *O. rufipogon* were evaluated as restorers for hybrid production using six CMS lines. The aim was to determine whether the introgressions led to high yield even in hemi- or heterozygous state as in hybrids. Some 67 hybrids were made between six CMS lines and 27 KMR3-*O. rufipogon* ILs as restorers and were grown in a DRR field in three replicates of three rows. Data on 14 yield and yield-related traits of parents and hybrids were gathered along with those on hybrid KRH2 (IR58025A/KMR3) and five popular hybrids. The yield of 43 out of the 67 hybrids was showing >50% heterosis compared with that of KRH2. Heterosis for yield per plant ranged from 17.6% to 84.9% and heterobeltiosis from 18% to 77%. The 11 highest-yielding hybrids showed >40 g yield per plant. Seven of these 11 showed both flanking markers of sub-QTL3, three had one flanking marker of sub-QTL3, and one had a flanking marker of sub-QTL2 of *yld2.1* from *O. rufipogon*.

Introduction

Rice (*Oryza sativa*) is the major food crop and more than half of the world's population depends on rice for 80% of its food calorie requirements. Improvement of yield is a major thrust of crop improvement research to meet the increasing needs. Shrinking cultivable rice area, abiotic and biotic stresses, and future climate change pose challenges to rice breeders to further increase production and productivity. Several high-yielding varieties have been developed but hybrids offer a substantial yield increase, especially in irrigated favorable ecosystems. So far, hybrid rice has had limited impact in India. India produces around 99 million tons of rice from 43 million hectares while hybrid rice is grown in only 3% of the total rice-producing area (1.4 million ha). One reason could be the low yield advantage of released hybrids, which essentially should be 20–30% in order to make the rice hybrids more economically beneficial (Virmani

1996, Mahadevappa 2004). Currently, the highest-yielding rice hybrids are derived from intersubspecific crosses between indica and japonica.

The identification of yield-enhancing genes from wild rice offers the possibility of an added increase in the yield of rice hybrids (Xiao et al 1996). Hence, improvement of elite parental lines using wild species is worth exploring for yield enhancement. There are only two reports of parental line improvement using genes from wild species of rice (Liang et al 2004, Fu et al 2010) and both used a restorer line 9311. Liang et al (2004) used wild rice *O. rufipogon* to improve popular restorer line 9311 and many lines with yield-enhancing genes from wild rice were developed with high yield potential. Fu et al (2010) identified 38.5% of the QTLs originating from *O. rufipogon* showing a beneficial effect for yield-related traits, indicating that there are potentially novel alleles in common wild rice. Such improved restorer lines with new gene sources identified from *O. rufipogon* were used to transfer the useful genes into the genetic background of many elite breeding lines. There are no follow-up reports on the performance of hybrids obtained using wild rice introgressions.

Rice hybrids yield 15–20% more than conventional varieties. Developing elite cytoplasmic male-sterile lines or restorer lines can help increase heterosis in hybrids. So, this will be an effective way to introgress yield-enhancing genes from *O. rufipogon* into parental lines of rice for further yield improvement. KMR3 is a popular fertility restorer line used in the production of the popular Karnataka Rice Hybrid-2 (KRH2), a cross between IR58025A and KMR3. This is used as a hybrid check in the medium-duration group of multilocation trials of the All India Coordinated Rice Improvement Program (AICRIP). The long-term goal of the study was to improve the restorer KMR3 using introgressions from *O. rufipogon* to enhance the yield of the widely adaptable hybrid KRH2 and thus help in boosting rice yield.

Materials and methods

The yield QTL *yld2.1* identified from *O. rufipogon* (Marri et al 2005) was introgressed into restorer line KMR3 using marker-assisted backcrossing for three generations (Babu et al 2009). Some 260 BC_3F_2 plants derived from 500 BC_3 plants were tested for homozygosity of one to three consecutive loci within the QTL *yld2.1*. Fifty-five plants were homozygous for one or another of the eight sub-QTL regions delineated by eight simple sequence repeat (SSR) markers. Twenty-seven ILs were selected covering all the eight regions from the 55 homozygous plants used as restorers for developing hybrids.

These ILs were crossed with six CMS lines—IR58025A, IR79156A, APMS6A, APMS10A, CRMS32A, and PUSA5A—during kharif*,* 2007. In all, 67 hybrids along with the corresponding parental B lines (maintainers) were field evaluated in a randomized complete block design (RBD) with three replications during kharif 2008 at DRR using line × tester analysis. Five popular hybrids, KRH2, DRRH2, DRRH3, PA6201, and PA6444, were used as standard checks in the experiment. The hybrids of each CMS line with KMR3 were considered as controls. In each entry, five plants were randomly tagged from each replication and phenotypic observations were recorded for days to 50% flowering (on a plot basis), plant height (cm), leaf length (cm), leaf width (cm), tillers per plant, productive tillers per plant, panicle length (cm), panicle weight (g), spikelets per panicle, spikelet fertility percentage, 1,000-grain weight (g), and grain yield per plant (g). Genotype means were used for analysis of variance and heterosis was calculated according to Singh and Chaudhary et al (1985). Mid-parent heterosis and better-parent heterosis or heterobeltiosis were determined as outlined by Falconer and Mackay (1996). Standard heterosis was estimated as percent gain in yield per plant of the hybrid over the standard check, KRH2 (IR58025A × KMR3).

Results and discussion

Two plants having the segment of yield QTL *yld2.1* (P-26 and P-105) were selected from the 251 BC_2 testcross progenies that were derived from the cross IR58025A/*O. rufipogon*// IR580325B///IR58025B////KMR3. The selected plants were crossed three times with KMR3, which gave 504 BC_3F_1 plants, and these plants were selfed to obtain BC_3F_2 individuals. Of these, 55 plants had homozygous alleles for *O. rufipogon* with the eight polymorphic markers lying within the QTL *yld2.1* region. Thus, the *yld2.1* region having eight polymorphic markers was divided into seven sub-QTL regions (sub-QTL1 to 7) (Fig 1). Twenty-seven selected high-yielding introgression lines were used to develop hybrids.

QTL Cartographer-based analysis using phenotypic and genotypic values of 55 homozygous plants with different sub-QTLs indicated a significant positive association of sub-QTL3 with yield per plant and the major yield-contributing traits grain weight per panicle, panicle length, number of tillers, and number of productive tillers (Fig. 2). The sub-QTL3 region flanked by RM3688 and RM3762 made a significant contribution to yield when derived from *O. rufipogon* compared with other sub-QTL regions.

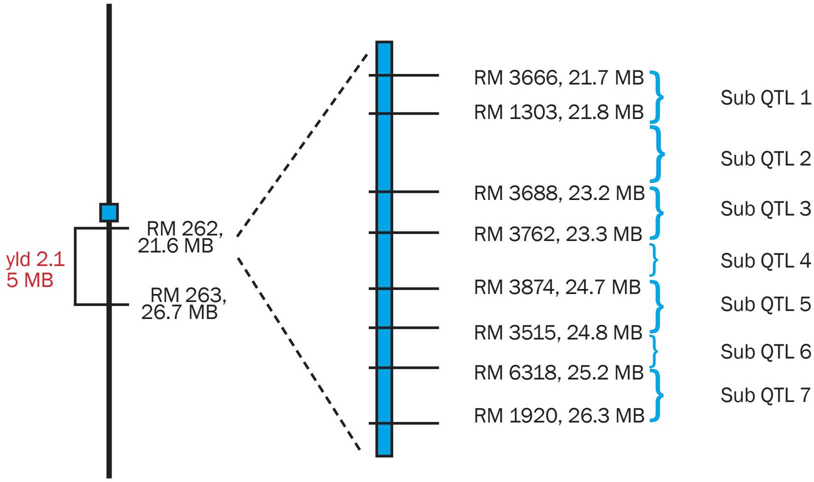

Fig. 1. Eight markers located between RM262-RM263 flanking *yld 2.1* and polymorphic between KMR3 and *O. rufipogon*. Some 504 BC_3F_1 plants were tested with these 8 polymorphic loci.

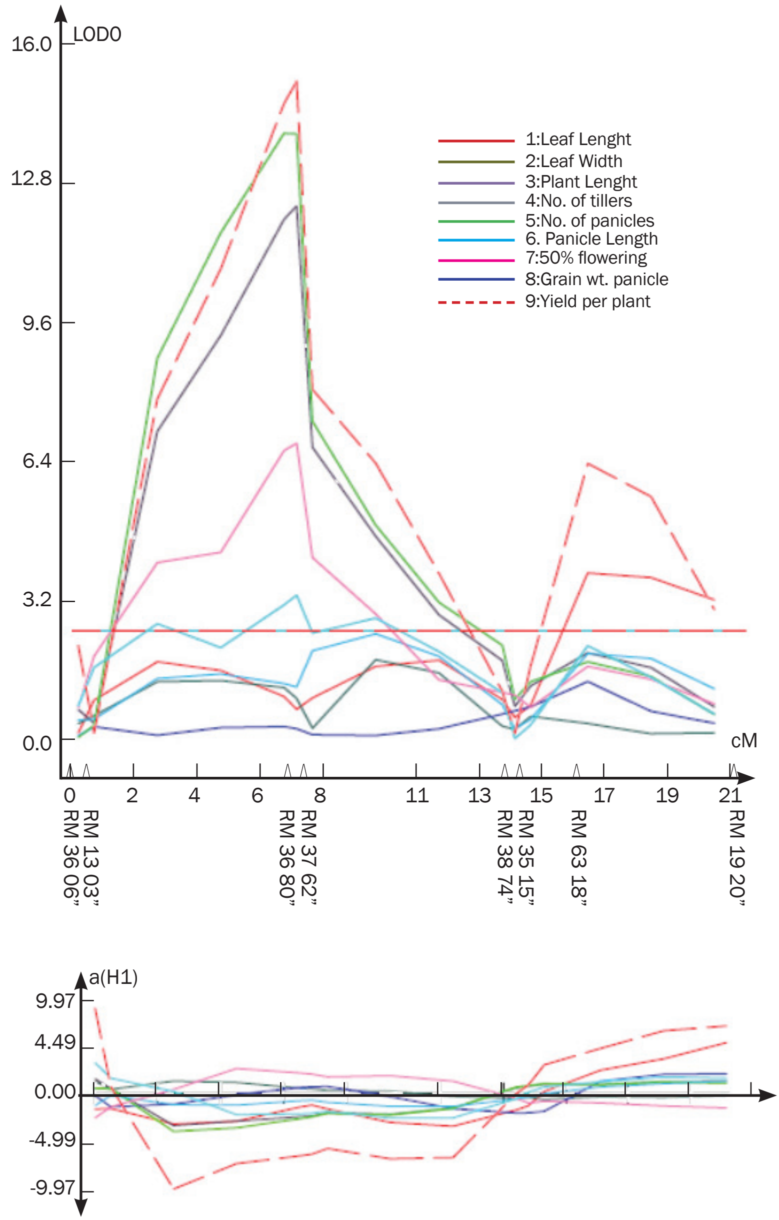

Fig. 2. QTL analysis, with graph showing additive effect for nine traits and corresponding eight markers within *yld2.1*.

Thus, the yield-enhancing QTL *yld2.1* was narrowed down to sub-QTL3 flanked by RM3688-RM3762 from 5 Mb to approximately 61 kb and this region has 10 open reading frames (ORFs). The candidate ORF is Os02g0582300, which codes for fertility restorer homologue A. The major fertility restorer genes *Rf3* and *Rf4* for the wild abortive CMS system were confirmed to be present in 27 KMR3-derived high-yielding ILs using closely linked microsatellite markers RM6100 and RM10313, respectively. Pollen fertility ranged from 74% (IL91-9) to 89% (IL50-10, IL86-8, and IL410-5). Spikelet fertility ranged from 73% (IL232-21) to 82% (IL363-12) compared with 79% in KMR3.

Mean heterosis, heterobeltiosis, and standard heterosis were estimated in 67 hybrids for 14 yield and yield-related characters during kharif 2008. Twenty-seven testers, that is, KMR3 ILs having different sub-QTL regions, were used as male lines in crosses with six CMS lines to develop hybrids for estimating heterosis. The yield of 43 out of the 67 hybrids showed >50% heterosis. Heterosis for yield per plant ranged from 17.6% to 84.9% and heterobeltiosis from 18% to 77%. The 11 highest-yielding hybrids showed >40 g yield per plant. Seven of these 11 hybrids showed both flanking markers of sub-QTL3, three had one flanking marker of sub-QTL3, and one had a flanking marker of sub-QTL2 of *yld2.1* from *O. rufipogon* (Table 1). As many as 61 hybrids exhibited significant positive mid-parent heterosis ranging from 17.4% (PUSA5A*50-13) to 84.9% (IR58025A*50-12) and 36 hybrids showed significant positive heterobeltiosis over their respective better parents, with a range from 18.5%

Table 1. Sub-QTL3 from *O. rufipogon* present in 7 of the top 11 hybrids out of 67. DRRH3 is a recently released hybrid.

Hybrids	Yield/ plant (g)	Days to 50% flowering	No of secondary branches	Panicle weight (g)	Markers/sub-QTLs in restorer line
APMS6A r * 363-12	**48.06**	71	47.0	3.82	**sub-QTL3**
CRMS32A * 50-10	**46.73**	74	51.6	4.66	RM 3762
APMS6A * 86-8	**44.80**	70	49.1	3.62	**sub-QTL3**
APMS6A * 86-18	**43.80**	68	44.7	3.63	**sub-QTL3**
IR79156A * 50-13	**43.47**	72	47.7	3.99	**sub-QTL3**
IR58025A * 50-12	**42.47**	72	51.6	4.11	**sub-QTL3**
IR79156A * 86-18	**42.33**	80	52.8	4.01	**sub-QTL3**
APMS6A * 410-5	**41.73**	69	53.5	3.96	RM 3688
APMS6A * 363-8	**40.26**	70	49.7	3.72	**sub-QTL3**
APMS6A * 91-15	**40.20**	75	62.5	3.67	RM 1303
CRMS32A * 410-5	**40.00**	68	46.0	3.66	RM 3688
Checks					
KRH2	28.30	79.0	46.0	3.4	
DRRH2	26.90	77.3	41.7	2.8	
DRRH3	**38.30**	**79.3**	**64.9**	**4.5**	
PA6201	28.90	79.3	41.3	2.7	
PA6444	26.80	75.0	46.6	3.0	
GK5003	30.10	71.3	41.9	3.4	

(PUSA5A*86-18) to 77.4% (IR58025A*50-12). Standard heterosis over KRH2 ranged from 19.6% (PUSA5A*363-5) to 65.3% (CRMS32A*50-10). Some of the hybrids with five ILs (IL50-7, IL50-13, IL50-12, IL86-18, and IL363-5) showed high standard heterosis (Table 2). Most of the restorers (KMR3 ILs) which had loci RM3688 and RM3762 flanking the target sub QTL3 from *O. rufipogon* showed high heterosis over KRH2. Standard heterosis over DRRH2 ranged from 14% (IR58025A*50-12) to 79% (APMS6A*363-12). Standard heterosis over DRRH2 ranged from 22.8% (IR58025A*50-13) to 50.2% (IR79156A*50-13) and standard heterosis over PA6201 ranged from 17.9% (IR58025A*50-13) to 66.1% (APMS6A*363-12). Based on data from 67 crosses, the top six KMR3 ILs identified are, 363-12, 50-10, 50-13, 50-12, 86-18, and 410-5, which show high combining ability (data not shown) and heterosis. In addition, the cross CRMS32A*363-5 gave hybrids with finer grains than the grains of the check hybrids. It is noteworthy that all six of these KMR3 ILs had one or both of the flanking markers of yield sub-QTL3 from *O. rufipogon.* Thus, sub-QTL3 appears to be effective in increasing yield not only in the homozygous state but also in the heterozygous state as in hybrids provided combining ability is good.

The exploitation of hybrid vigour depends on the per se performance of hybrids and also the degree of heterosis. The degree of heterosis was estimated over the mid-parent, better parent, and standard hybrid. The mean performance of lines, testers, and their hybrids indicates the value of genetic variability for the improvement of yield and related traits. Among the maintainer lines, APMS6B exhibited significantly higher yield (27.3 g/plant) than the grand mean (25.4 g/plant) of all the lines tested. Among the testers (restorers), IL50-7 (30.4 g/plant), IL50-13 (29.9 g/plant), IL86-18 (29.5 g/plant), IL363-5 (28.8 g/plant), and KMR3 (28.2 g/plant) showed significantly higher yield than the grand mean yield (25.4 g/plant). Of the 36 hybrids, 16 hybrids showed significantly higher yield than the grand mean yield (35.5 g/plant) and also a higher mean than KMR3-derived hybrids (Table 3). APMS6A/IL86-18 yielded 43.47 g compared with 31.98 g for APMS6A/KMR3, CRMS32A/IL50-7 yielded 41.48 g compared with 37.60 g for CRMS32A/KMR3, and IR79156A/IL86-18 yielded 42.22 g compared with 36.61 g for IR79156A/KMR3.

Table 2. High standard heterosis in hybrids from KMR3 ILs compared with KMR3.

CMS line	Mean heterosis (%)		Heterobeltiosis (%)		Standard heterosis (%)	
	KMR3	ILs	KMR3	ILs	KMR3	ILs
IR58025A	41.3	29.9–84.9	25.7	14.5–77.4	12.2	22.8–58.0
APMS6A	23.5	23.2–54.0	21.4	20.0–48.3	27.7	28.7–63.0
CRMS32A	27.0	24.0–40.0	15.3	9.5–35.3	21.3	20.6–39.0
IR79156A	33.8	26.0–70.0	16.5	9.4–59.0	22.5	41.1–61.7
APMS10A	18.8	17.0–35.0	14.6	8.0–60.1	20.6	20.3–42.6
PUSA5A	33.5	15.0–54.4	11.5	0.4–31.4	12.6	13.6–30.2

Table 3. Mean yield per plant (g) in parents, control hybrid, and hybrids derived from crosses between six CMS lines and five introgression lines, with hybrids with KMR3 as the control. The values are means of three replicates.[a] The yield of R lines = testers (T) is in red and the yield of the maintainer lines of cms lines (L) is in blue.

CMS lines (L) \ R lines (T)		KMR3	IL50-7	IL50-13	IL50-12	IL86-18	IL363-5	Mean
		28.27	30.40	29.93	23.93	29.53	28.80	28.48
IR58025A	22.00	**35.03**	36.48	35.82	36.35	38.40*	30.53	35.44
APMS6A	27.33	31.99	35.19**	34.35	31.60	43.47***	30.55	34.52
CRMS32A	23.07	37.61	41.48**	37.34	32.75	38.07	31.47	36.45
IR79156A	20.93	36.62	36.28	40.44	33.32	42.22*	35.00	37.31
PUSA5A	22.67	38.02	32.19***	33.68**	33.77***	31.35***	32.09***	33.52
APMS10A	18.67	32.92	35.51*	34.24*	33.49	32.62	30.18*	33.16
Mean	22.44	35.36	36.19	35.98	33.55	37.69	31.64	35.07

[a]* = P<0.05; ** = P<0.01; *** = P<0.001, negatively significant, L = line/CMS line, T = tester/restorer line, parent mean= maintainer lines (B) of respective CMS lines were used for measuring yield, KRH2 yield in bold.

Conclusions

It is essential to improve parental lines with superior traits to enhance the performance of hybrids. When a restorer line that expresses a main-effect QTL is bred, it could be used in a number of cross combinations and it is a valuable target for gene manipulation and for further application in rice breeding (You et al 2006). Superior parental lines favorably enhance the performance of hybrid rice derived from many combinations, indicating that some large-effect QTLs may affect the performance of both parental lines and hybrids. These studies have clearly shown the occurrence of significant heterosis, heterobeltiosis, and standard heterosis in plants having sub-QTL3. The increase in yield of F_1 hybrids showing significant standard heterosis in the three replicated yield trials ranged from 19.6% to 66.1%. The high heterotic F_1 hybrids may be attributed to their parents that were specifically selected on the basis of their higher per se yield. 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 primarily depends on the potential value of their parents.

On the basis of mean performance, heterosis, and heterobeltiosis estimates, six KMR3 ILs (363-12, 50-10, 50-13, 50-12, 86-18, and 410-5) were identified as better male lines than KMR3. We conclude that KMR3 lines with sub-QTL3 restored fertility and increased yield to a greater extent than the lines carrying other sub-QTLs. Fine mapping of sub-QTL3 is in progress.

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Notes

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Application of an *S5* functional marker system in intersubspecific hybridization to improve heterosis

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Rice is one of the most important food crops in the world. Of the total of 24 species of the genus *Oryza*, only *Oryza sativa* and *O. glaberrima* are cultivated in Asia and Africa, respectively. During the course of evolution, the Asian cultivated rice (*O.sativa*) was differentiated into two distinct eco-geographic races or subspecies, indica and japonica (Kato et al1928). In the same way, the Chinese have recognized two rice varietal groups, Hsien (indica) and Keng (japonica) (Khush1997). Based on morphological characters and geographic distribution, Matsuo (1952) classified cultivated rice into three types: japonica, javanica, and indica. Indica rice is generally adapted to the humid regions of the tropics and subtropical Asia (India, China, Vietnam, Thailand, Myanmar, the Philippines, Bangladesh, and Sri Lanka, etc.) whereas japonica rice is adapted to the temperate regions (Korea, Japan, and northern China, Taiwan, parts of Australia, California, Europe, and Egypt, etc.). Also, a third small group called tropical japonica (or javanica) is mainly found in the equatorial region of Southeast Asia, particularly Java and Indonesia). Rice breeders in tropical Asia, impressed by the relatively higher yielding ability of japonica varieties, attributable to semitall stature and hence lodging resistance and higher responsiveness to higher doses of fertilizer, believed that recombining of such yield-promoting features of japonica with wide adaptability and good grain quality of indicas could raise the yield of tropical rice, which had been stagnating for a long time at low yield (Yuan 1994).

The major problem, however, in exploiting intersubspecific heterosis is hybrid semisterility. The discovery of wide compatibility (WC) genes by Ikehashi and Araki (1986) paved the way for exploiting indica/japonica heterosis in rice (Yuan 1994). Varieties possessing WC genes are called wide compatibility varieties (WCV) that produce a normal fertile hybrid when crossed with either indica or japonica. Based on the results of WC variety inheritance studies, Ikehashi and Araki (1986) proposed a genetic model to account for wide compatibility. According to this model, there are three alleles at the *S5* locus: neutral$S5^n$; indica$S5^i$, and japonica$S5^j$. A zygote formed from the $S5^n$ allele with either of the other two alleles, $S5^n/S5^i$or$S5^n/S5^j$, would be normal fertile, while a zygote with genotype $S5^i/S5^j$ would be partly sterile. Using morphological markers, Ikehashi and Araki (1986) also found the *S5* locus located near the C^+ locus on chromosome 6. This chromosomal location has been further confirmed by several studies using isozyme and molecular markers (Li et al 1991, Liu et al 1992, Zheng et al 1992, Yanagihara et al 1995).

Conventionally, WC varieties are identified by testcrossing and evaluating the spikelet fertility of F_1s. This is a tedious and time-consuming process and it is also often inconclusive. The use of molecular markers can overcome these limitations. With the availability of molecular markers, genetic linkage maps, and genome sequences in rice, the major gene *S5* was recently cloned by Chen et al (2008) using a map-based cloning approach and this showed that *S5* encodes an aspartic protease conditioning embryo-sac fertility and *indica* and *japonica* alleles differ by two nucleotides. A discontinuous 136-bp deletion that was separated by a TAAT motif in the first exon of the gene encoding aspartic protease was reported in WC varieties carrying a neutral allele compared with the *indica* and *japonica* allele. This large deletion has led to subcellular mislocalization of the encoded protein that resulted in its nonfunctionality in WC varieties carrying $S5^n$. Sundaram et al (2010) developed a PCR-based co-dominant *S5*functional multiplex marker system (S5-MMS) to detect a neutral allele carrying deletion and an *indica* and *japonica* allele carrying SNPs in a single PCR tube reaction by multiplexing. In our investigation, we used the S5 multiplex marker system to identify potential genetic resources for wide compatibility for use in hybrid rice breeding.

Materials and methods

A total of 300 tropical *japonica* accessions provided by the International Rice Research Institute (IRRI) and seven *indica* genotypes (Swarna, CSR36, APMS6A, APMS6B, CST 7-1, Improved SambhaMahsuri, and Sampada) underwent molecular screening for the presence of a WC*S5* neutral allele. Some 150 F_1 hybrids were generated using seven *indica* genotypes as female parents and tropical *japonica* genotypes as male parents. These F_1s were grown at Ramachandra Puram, a DRR farm on the ICRISAT campus, during the rabi season (November 2011-March 2012) and F_1s were evaluated for their spikelet fertility.

Spikelet fertility

The panicles that emerged from the primary tiller were bagged before anthesis to avoid outcrossing and the number of filled grains and chaffs in the panicle were counted at the time of maturity. The ratio of filled grains to the total number of spikelets, expressed as spikelet fertility percentage, is as follows:

$$\text{Spikelet fertility (SPF) \%} = \frac{\text{Number of filled spikelets in the panicle}}{\text{Total number of spikelets in the panicle}} \times 100$$

Plants were classified into four classes based on spikelet fertility percentage: fertile (more than 75% spikelet fertility), partially fertile (51–75%), partially sterile (1−50%), and completely sterile (0%).

Genotyping: DNA isolation and PCR analysis

Total genomic DNA was isolated from 20-day-old young leaves of all the genotypes by a mini-preparation method (Dellaporta et al 1983). PCR was carried out using 25−30 ng/µL of template DNA containing 2.5 mM of each dNTP, 0.25 µM of each forward and reverse primer, 1 U of Taq DNA polymerase, and 1X PCR buffer in a total volume of 10 µL in a thermal cycler (Eppendorf, USA). The cycling conditions were an initial denaturation at 94°C for 5 min followed by 30 cycles of PCR amplification under the following parameters: 30 sec at 94°C, 30 sec at 55°C, and 1 min at 72°C, followed by a final extension at 72°C for 5 min.The amplified PCR products along with a 100-bp molecular marker (Bangalore Genie, India) were separated on a 3.0% Seakem® LE agarose gel (Lonza, USA), stained with ethidium bromide and documented using the Gel documentation system (Alpha Innotech, USA). Based on the banding pattern, gels were scored for the presence and absence of bands as restorers and nonrestorers. Table 1 presents the sequence of primers and their amplification product sizes.

Results and discussion

A total 325 genotypes, including tropical japonica genotypes and indica genotypes, underwent molecular screening to assess the allelic status of the *S5* locus. Out of 325 genotypes tested, 90 tropical japonica genotypes were identified to carry an *S5* neutral allele and an indica genotype, Swarna, was also identified to carry an *S5* neutral allele. The list of WC genotypes possessing an *S5* neutral allele identified with the help of an S5-InDel SSR marker appears in Table 2. A total of 150 intersubspecific hybrids were generated by crossing indica genotypes as female parents and tropical japonica genotypes as male parents. F_1s were raised during the next season to evaluate their spikelet fertility percentage. Phenotyping for spikelet fertility ranged from 4% to 97%as partial sterility to complete fertility. Genotyping of F_1s for their S5 allele status was done with the help of S5-MMS.Heterozygosity of the F_1s was confirmed with the help of amultiplex marker system and the results appear in Figure 1.

Table 1. List of S5-MMS primer sequences.

Name of primer[a]	Sequence (5' to 3')	Amplification product size (bp)		
		Indica	Japonica	Neutral
S5-InDel F				
S5-InDel R			417	281
S5-ELSP F		417		
S5-IASP 2	CCTACGTTTGACTGCCTGCCTG			
S5-JASP 1	CTACACGCGGCTTCGGGAAAGC			
S5-ELSP	GACAGCAGCATCAACGACTTCC	527	No amplification	527
	TCGTCAGTGGGCAAGCAGTAGCTG			
	ACCCTGATATTCTGAGTTACAAGGCATTA			
	GCTCTTGATGTCCGGTGATACC			
		No amplification	325	No amplification

[a]InDel = insertion/deletion; ELSP = external locus-specific primer; IASP = indica allele-specific primer; JASP = japonica allele-specific primer.

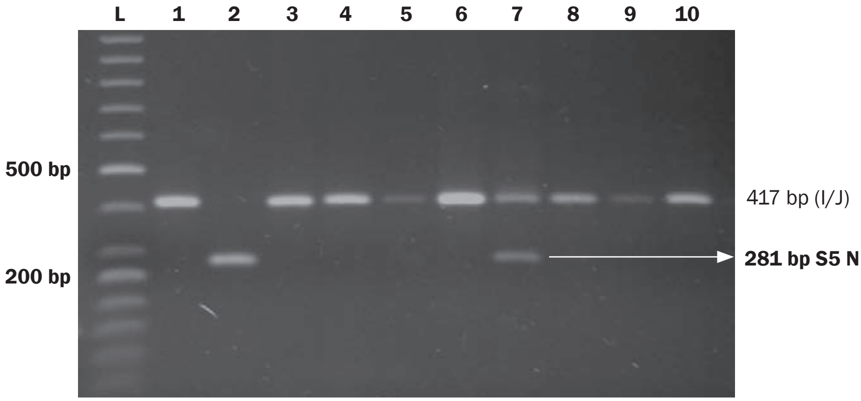
Table 2. List of wide compatibility genotypes possessing *S5ⁿ* identified by S5-indel SSR marker.

S. no.	IRGC ID	Name of variety	WC S5nstatus
1	IRGC137	Sunbonnet	$S5^n$
2	IRGC138	Bluebonnet	$S5^n$
3	IRGC143	Rexoro	$S5^n$
4	IRGC144	Texas Patna	$S5^n$
5	IRGC289	Azmil85	$S5^n$
6	IRGC238	Azucena	$S5^n$
7	IRGC1715	Rexoro	$S5^n$
8	IRGC1797	Texas Patna	$S5^n$
9	IRGC1811	Bluebonnet-50	$S5^n$
10	IRGC1943	Rexar Rogue	$S5^n$
11	IRGC1972	Rexark Rogue	$S5^n$
12	IRGC3255	Mojito Colorado	$S5^n$
13	IRGC3764	Asse-Y-Pung	$S5^n$
14	IRGC3849	Kinastano	$S5^n$
15	IRGC4020	Pilawan	$S5^n$
16	IRGC4122	IguapeCateto	$S5^n$
17	IRGC5441	-	$S5^n$
18	IRGC5766	Pato de Gallinazo Y	$S5^n$
19	IRGC6226	Bluebonnet-50	$S5^n$
20	IRGC6309	Nira	$S5^n$
21	IRGC7756	Vegold	$S5^n$
22	IRGC8146	Saba	$S5^n$
23	IRGC8182	MalagkitPirurtong	$S5^n$
24	IRGC10658	Cuba-65	$S5^n$
25	IRGC10739	PI-303646	$S5^n$
26	IRGC10760	583	$S5^n$
27	IRGC11821	Peek	$S5^n$
28	IRGC12052	Bomalasang	$S5^n$
29	IRGC13496	C-8434	$S5^n$
30	IRGC14917	280	$S5^n$
31	IRGC15006	Khao Hang	$S5^n$
32	IRGC15023	Lai	$S5^n$
33	IRGC16073	Plate Blanc MN 1	$S5^n$
34	IRGC16081	Gbante	$S5^n$
35	IRGC17051	Chuan3	$S5^n$
36	IRGC17704	GundelBatu	$S5^n$
37	IRGC23385	Khao Dam	$S5^n$
38	IRGC23423	KhaoKap Sang	$S5^n$
39	IRGC23729	Hanrm Om	$S5^n$
40	IRGC24274	Labelle	$S5^n$
41	IRGC24528	Bonnet-73	$S5^n$
42	IRGC25954	Belle Patna (Uruguay)	$S5^n$
43	IRGC25966	Cana Roxa	$S5^n$
44	IRGC26178	Star Bonnet	$S5^n$
45	IRGC26276	Bikyat	$S5^n$
46	IRGC26940	Ngup-Per	$S5^n$
47	IRGC27129	GundilKuning	$S5^n$
48	IRGC27428	PulutSampaka	$S5^n$

continued

Table 2. Continued.

S. no.	IRGC ID	Name of variety	WC $S5^n$ status
49	IRGC27435	PulutTodopi	$S5^n$
50	IRGC29772	Khao Do Jgoi	$S5^n$
51	IRGC30921	D1-177	$S5^n$
52	IRGC31051	D4-136	$S5^n$
53	IRGC31063	D4-148	$S5^n$
54	IRGC33130	Indane	$S5^n$
55	IRGC39111	1-52-6	$S5^n$
56	IRGC44455	Inmarang	$S5^n$
57	IRGC47345	Tapungol (White)	$S5^n$
58	IRGC50531	Pacholinha	$S5^n$
59	IRGC63248	GBE Dasima	$S5^n$
60	IRGC67431	Dinolores	$S5^n$
61	IRGC67437	Inuway	$S5^n$
62	IRGC74607	KinandanagRusiksik	$S5^n$
63	IRGC74613	Minatanda	$S5^n$
64	IRGC117255	Miramono	$S5^n$
65	IRGC1172456	TOS-5790	$S5^n$
66	IRGC117359	WAB-368-B-1-H1-HB	$S5^n$
67	IRGC33016	Chinsaba	$S5^n$
68	IRGC19928	Chesiviruppu	$S5^n$
69	IRGC26913	Kola Nata 1-24	$S5^n$
70	IRGC37015	Bhirpala	$S5^n$
71	IRGC71598	PurakSiriba	$S5^n$
72	IRGC47216	Gobyerno	$S5^n$
73	IRGC47248	Kinyo	$S5^n$
74	IRGC50399	Nambol	$S5^n$
75	IRGC50448	Canela de Ferro	$S5^n$
76	IRGC50865	Mahapleu(504)	$S5^n$
77	IRGC51099	L-201	$S5^n$
78	IRGC51125	Blue Belle	$S5^n$
79	IRGC53200	Matahambre	$S5^n$
80	IRGC55403	Tabuno (White)	$S5^n$
81	IRGC55808	Oriente-10	$S5^n$
82	IRGC57184	PeletBandisa	$S5^n$
83	IRGC57692	Kosagi	$S5^n$
84	IRGC60310	Kendinga-5(H)	$S5^n$
85	IRGC62162	Botpa Bara	$S5^n$
86	IRGC62171	Kamja	$S5^n$
87	IRGC66759	Sky Bonnet	$S5^n$
88	IRGC67423	Aguyod	$S5^n$
89	IRGC67846	Ondeykam	$S5^n$
90	IRGC69058	TAI-6	$S5^n$
91	Indica genotype	Swarna	$S5^n$



L-100 bp ladder, I/J-*indica*-or *japonica*-specific allele

Fig. 1. Molecular screening using S5-indel marker.

Three categories of intersubspecific hybrids have been observed: hybrids with high spikelet fertility with the presence of an *S5* neutral allele, hybrids with low SPF% without $S5^n$, and hybrids with low SPF% with $S5^n$. A few hybrid combinations with low to high spikelet fertility with or without an *S5* neutral allele are presented in Table 3. A few intersubspecific hybrids without the presence of an *S5* neutral allele showed higher fertility, indicating that some other neutral alleles are involved in overcoming partial sterility of intersubspecific hybrids. A few hybrid combinations showed high hybrid sterility with the presence of an *S5* neutral allele, which explains the existence of other than an embryo sac sterility mechanism of indica by japonica crosses, since $S5^n$ overcomes only embryo sac hybrid sterility. Liu et al (1992) reported that the*S5* neutral allele overcomes only embryo sac sterility and it is not sufficient to overcome indica-japonica hybrid sterility completely. In rice, around 50 loci controlling indica-japonica hybrid sterility and wide compatibility have been identified, including loci causing female gamete/embryo sac abortion and pollen sterility (Ouyang et al 2009). Our study results are in agreement with earlier reports that many loci are involved in controlling wide compatibility and that the *S5* neutral allele alone is not sufficient to overcome indica-japonica hybrid sterility.

To test the restoration ability of tropical japonica lines, APMS6A was crossed with 20 tropical japonica with $S5^n$ and these indica by japonica hybrids showed sterility to partial sterility, indicating that tropical japonica lines unable to restore the fertility of WA-CMS may be due to poor restoration ability or the presence of other sterility mechanisms. Virmani (2005) reported that restorer frequency in temperate and tropical japonica rice is negligible and, for the development of rice hybrids in a japonica genetic background, restorer lines have to be bred by transferring *Rf* genes from indica rice. Wei et al (2010) and Yang et al (2012) demonstrated that the*S5* neutral allele exists in wild rice and that *Oryza sativa* and *O. nivara* had $S5^n$ in the homozygous state ($S5^n$ $S5^n$), whereas *O. rufipogon* had it in the heterozygous state ($S5^n$ $S5^i$ or $S5^nS5^j$). To validate these results, with the help of a PCR-based S5 multiplex marker system, around 20 *O. rufipogon* accessions were screened and, surprisingly, all 20 *O. rufipogon*

Table 3. Spikelet fertility percentage and S5n allele status of intersubspecifichybrids.[a]

Indica × tropical japonica hybrids	Spikelet fertility percentage	Phenotypic visual observation	S5 neutral allele status
Swarna ×IRGC117255	97	F	$S5^n$
Swarna ×IRGC67614	92	F	$S5^n$
CSR-36 ×IRGC25966	77	F	$S5^n$
Sampada ×IRGC39111	87	F	$S5^n$
RP BIO 226 ×IRGC23385	76	F	$S5^n$
RP BIO 226 ×IRGC74613	78	F	$S5^n$
CSR-36 ×IRGC48960	77	F	Absent
RP BIO 226 ×IRGC69708	76	F	Absent
Sampada ×IRGC11010	79	F	Absent
Sampada ×IRGC69861	83	F	Absent
CST-7-1 ×IRGC63248	93	F	Absent
APMS 6 B ×IRGC69708	91	F	Absent
RP BIO226 ×IRGC25966	40	PF	$S5^n$
RP BIO226 ×IRGC26940	22	PS	$S5^n$
Sampada ×IRGC67431	37	PS	$S5^n$
Sampada ×IRGC44455	34	PS	$S5^n$
APMS6A ×IRGC23385	33	PS	$S5^n$
APMS6A ×IRGC48960	15	S	$S5^n$
APMS6A ×IRGC63121	24	S	–
APMS6A ×IRGC63248	17	PS	–

[a]F =fertile, S =sterile, PS = partially sterile, PF =partially fertile.

accessions were identified to carry $S5^n$ in the heterozygous state (Fig. 2). These results confirm that an *S5* neutral allele might have evolved from *O. rufipogon*.

An F_2 population of Swarna ×IRGC48960 was subjected to genotyping with the help of the S5 multiplex marker system. Of 155 plants, 38 showed a Swarna parent-type amplification of the *S5* neutral allele presence, 41 plants showed an IRGC48960 genotype amplification pattern of the japonica allele, and 76 plants showed a heterozygous pattern of amplification explaining the 1:2:1 segregation ratio of a perfect F_2 ratio. The amplification pattern of S5-MMS in an F_2 population appears in Figure 3.

To conclude, the S5 multiplex marker system is a powerful PCR-based low-cost, highly efficient marker system for identifying WC genotypes carrying the*S5* neutral allele from germplasm lines, different mapping populations, and wild genomes. It saves breeders one year of valuable time in evaluating testcrosses for producing intersub-

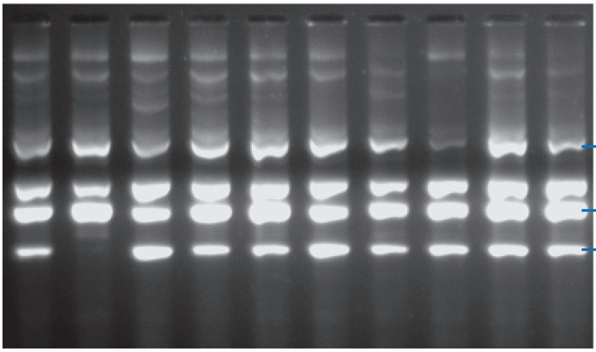
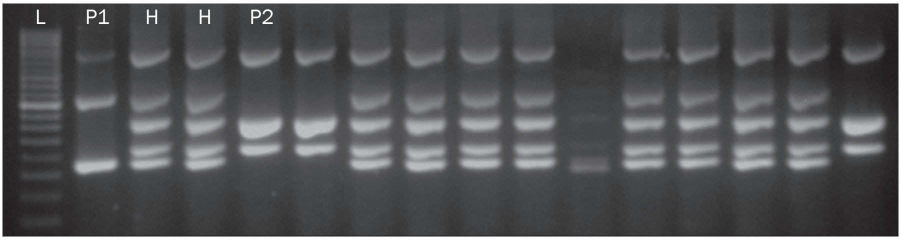


Fig. 2. *S5* multiplex marker system of *Oryza rufipogon* accessions.



L = ladder, P1 = Swarna, P2 = IRGC48960, H = heterozygous

Fig. 3. Genotyping of F_2 population of Swarna × IRGC48960.

specific hybrids. This S5-MMS is a very useful tool for incorporating the *S5* neutral allele into elite indica or japonica lines for their use in intersubspecific hybridization.

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Multiplex PCR-based detection of *Xanthomonas oryzae* pathovars from rice seeds—applying a molecular tool to facilitate global movement of "clean" rice seeds

M.H.R. Nguyen, M.R.G. Burgos, J. Lang, B. Cottyn, V. Verdier, D. Mishra, Y. Raj, J.E. Leach, and C.M. Vera Cruz

The inclusion of *Xanthomonas oryzae* pathovars *oryzae (Xoo)* and *oryzicola (Xoc)*, causal organisms of bacterial blight and bacterial leaf streak, respectively, as select agents calls for a universally accepted protocol for their detection. This is very important in facilitating global movement of rice seeds. This study aims to develop a method to detect these pathogens from seeds, which incorporates the use of diagnostic multiplex PCR primers developed by Lang and co-workers in 2010. The development and refinement of the protocol focus on the preparation of extracts from seed samples in a simple and cost-effective manner, which can still obtain reliable results. The developed protocol provides flexibility to users, with an option for pathogen detection without bacterial isolation, termed "direct assay," involving sonication, addition of sodium sulfite (Na_2SO_3) and polyvinylpolypyrrolidone (PVPP), filtration, and freezing to obtain PCR-ready samples. When applied to artificially inoculated seeds and seeds from naturally infected plants, *Xoo* DNA is detected from the latter after 10 months of storage at room temperature and at 4 ^oC. The other option combines multiplex PCR and microbiological methods to isolate, identify, and confirm virulence of the pathogens. Twenty-four participants involved in germplasm-related work from 13 countries validated the qualitative assay during a training-workshop conducted to harmonize detection strategies for the two pathogens. Providing a validated, standard protocol for detecting these pathogens from rice seeds ensures proper comprehension by end-users, whether the technology is employed in quarantine, research, or institutions involved in the global movement of rice seeds.

Xanthomonas oryzae pathovars *oryzae* (*Xoo*) and *oryzicola* (*Xoc*), causal organisms of bacterial leaf blight and bacterial leaf streak, are regulated pathogens. Established guidelines and protocols are strictly followed to prevent the spread of these bacterial pathogens. However, there is still a need for a standard assay for these regulated pathogens, a universally accepted protocol applicable for use by regulatory bodies and quarantine laboratories around the world.

In this report, we present a qualitative PCR-based assay using a set of highly specific diagnostic primers for multiplex PCR, which can detect and distinguish *X. oryzae* at the pathovar level from rice seeds that can be employed alone as a direct assay for *X. oryzae* from seeds, or used in combination with classical (culture-based) methods for the detection of *X. oryzae* pathovars from seeds.

Relevance of a PCR-based detection protocol

Isolation of *X. oryzae* pathovars *oryzae* and *oryzicola* from rice seeds is difficult due to the highly diverse bacterial populations that inhabit the seeds. In addition, *Xoo* is particularly difficult to isolate because of (1) the low population of the pathogen in the seed, if present; (2) its slow growth in agar medium coupled with its poor competitive ability relative to other seed-associated bacteria; and (3) the presence of other yellow-pigmented bacteria that show colony morphology (see Fig. 1) similar to *Xoo* on agar media (*Xo* look-alikes).

Analysis of the genetic relationship (obtained from cluster analysis of BOX-PCR fingerprints) of 277 nonpathogenic *Xo* look-alikes isolated in IRRI's Seed Health Unit from samples of various seed lots revealed that none of the isolates clustered with *Xoo*/*Xoc*. The presence of these nonpathogenic *Xo* look-likes is particularly important in seed health testing, in which they can result in misidentification and wrong diagnosis. Therefore, other more discriminatory methods for detecting plant pathogenic bacteria in rice seeds should be designed. Existing methods for the detection and identification of bacterial pathogens include immunodiagnosis, genotypic approaches, and the integration of several methods for detection and identification (Alvarez 2004).

PCR-based detection: single and multiplex primers

The development of multiplex PCR primers for *Xoo* and *Xoc* (Table 1), which can differentiate the pathovars in one PCR reaction (Fig. 2), provides an alternative protocol to culture-based detection of *Xanthomonas oryzae*. Application of this technology to seed health testing led to the design of a method to recover PCR-ready seed extracts for multiplex PCR.

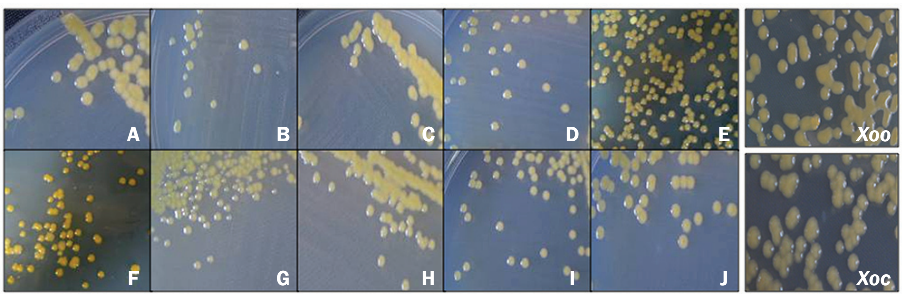


Fig. 1. Colony morphology of nonpathogenic *Xo* look-alikes (A–J) determined to be the most related to *Xoo* and *Xoc* at the genotypic level (80%) using cluster analysis of BOX-PCR fingerprints.

Table 1. Multiplex PCR primers for detection and differentiation of *Xanthomonas oryzae* pathovars *oryzae* and oryzicola (Lang et al 2010) in rice seeds.

Target	Name	Sequence (5′-3′)	Product size (bp)
X. oryzae	Xo3756F	CATCGTTAGGACTGCCAGAAG	331
	Xo3756R	GTGAGAACCACCGCCATCT	
X. oryzae pv. *oryzae*	Xoo281-8F	GCCGCTAGGAATGAGCAAT	162
	Xoo281-8R	GCGTCCTCGTCTAAGCGATA	
X. oryzae pv. *oryzicola*	Xoc3866F	ATCTCCCAGCATGTTGATCG	691
	Xoc3866R	GCGTTCAATCTCCTCCATGT	
	Xoc3864F	GTGCGTGAAAATGTCGGTTA	945
	Xoc3864R	GGGATGGATGAATACGGATG	

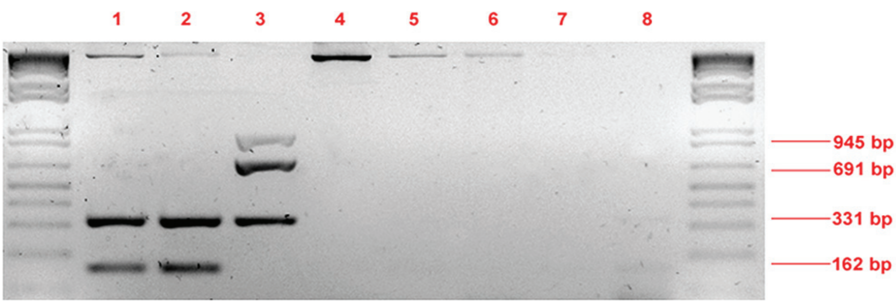


Fig. 2. Gel photo showing PCR amplification of *Xoo* and *Xoc* DNA fragments. Lane 1—PX099 (*Xoo*), lane 2—PX0339 (*Xoo*), lane 3—BLS256 (*Xoc*), lanes 4 to 7—selected *Xo* look-alikes (SHU261, SHU199, SHU166, SHU309), and lane 8—no template control.

Assay development

Since the detection strategy is PCR-based, an important consideration during assay development was optimizing the method of sample preparation—finding easier ways to recover the bacterial cells from the seeds with minimal introduction of PCR inhibitors to the seed extract that will be the source of DNA template for PCR. Crushing or macerating the seeds in PBS was shown to possibly introduce PCR inhibitors. Seed vortexing was thus tested as an alternative procedure.

Because of its potential as a convenient alternative to seed vortexing for analysis of numerous samples, sonication was also tested as a means to dislodge the target bacteria from the seed samples in the final stages of assay development (Fig. 3). Empirical data showed that cell recovery (estimated by aerobic plate counts) was similar for vortexing and sonication. However, in multiplex PCR, *Xo* DNA was detected from sonicated samples that were more diluted (tenfold difference) than vortexed samples (Fig. 4).

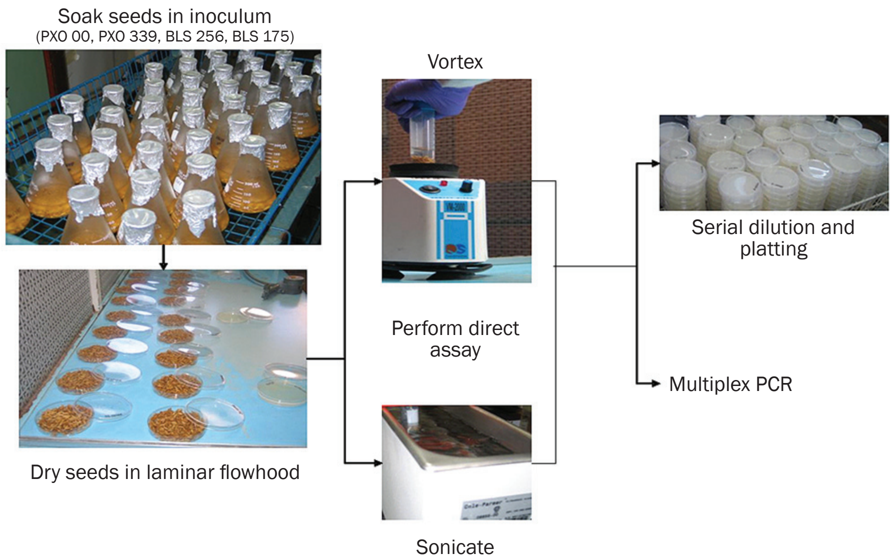


Fig. 3. Experimental setup to compare sonication and vortexing of samples as means to dislodge bacterial cells from rice seeds suspended in PBS.

Protocol validation

The developed assay was validated during a 5-day training-workshop on "Harmonizing detection of *Xo* pathovars from rice seeds," which targeted quarantine personnel. There were 24 participants from 13 countries: Agronomica and EMBRAPA, Brazil (2); DA Plant Quarantine Research Group, Thailand (2); USDA-APHIS (1); Australia (1); China (1); Colombia (2); India (2); Kenya (1); Mexico (1); Nigeria (1); Philippines (8); United States (1); and Vietnam (1). Topics discussed were traditional culture-based methods for the isolation and identification of bacteria, molecular tools for seed health testing and diagnostics, sampling methods, pathogenicity testing, and the application of these concepts in developing a protocol for the detection of *Xo* pathovars from seeds. Other than resource persons from IRRI, five resource persons came from Colorado State University, IRD, and China.

Participants were able to validate the beta version of the entire protocol and a harmonized protocol was agreed upon by all participants at the end of the workshop, revised as shown in Figure 5, and distributed to all participants after the workshop.

Conclusions

The detection protocol for *X. oryzae* pathovars from rice seeds enables the rapid detection of these pathogens without a need to plate and isolate the bacteria on agar media via a direct assay, and allows the integration of classical and molecular methods, which include isolation of the pathogen from seeds, optional biochemical characterization of

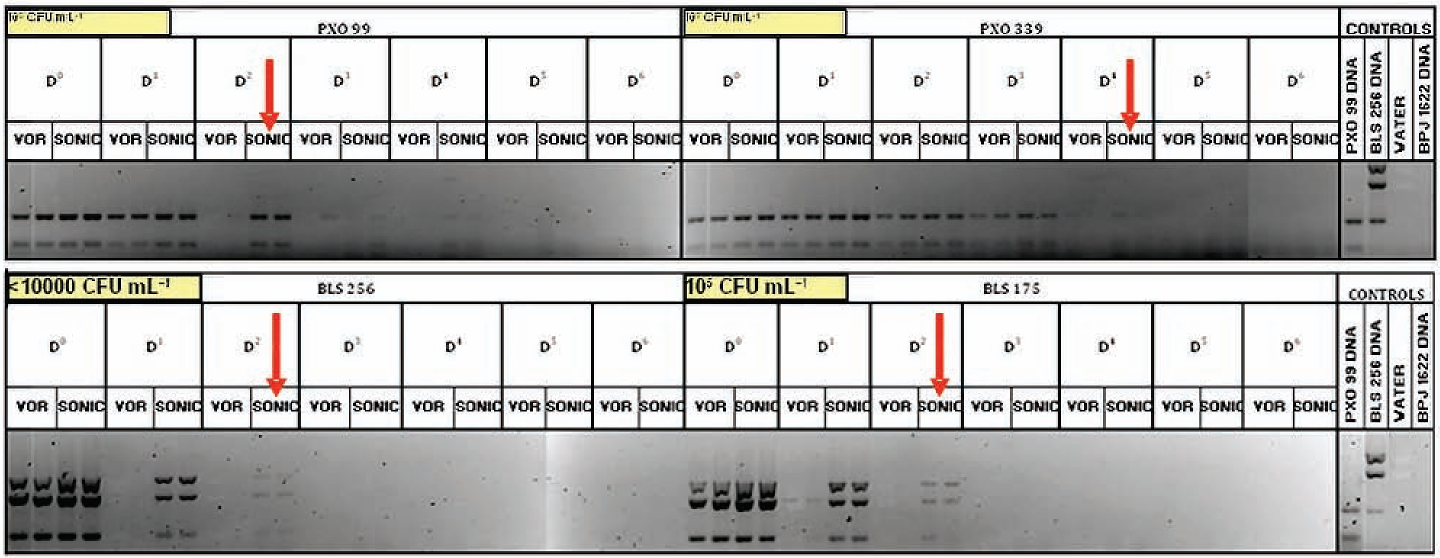
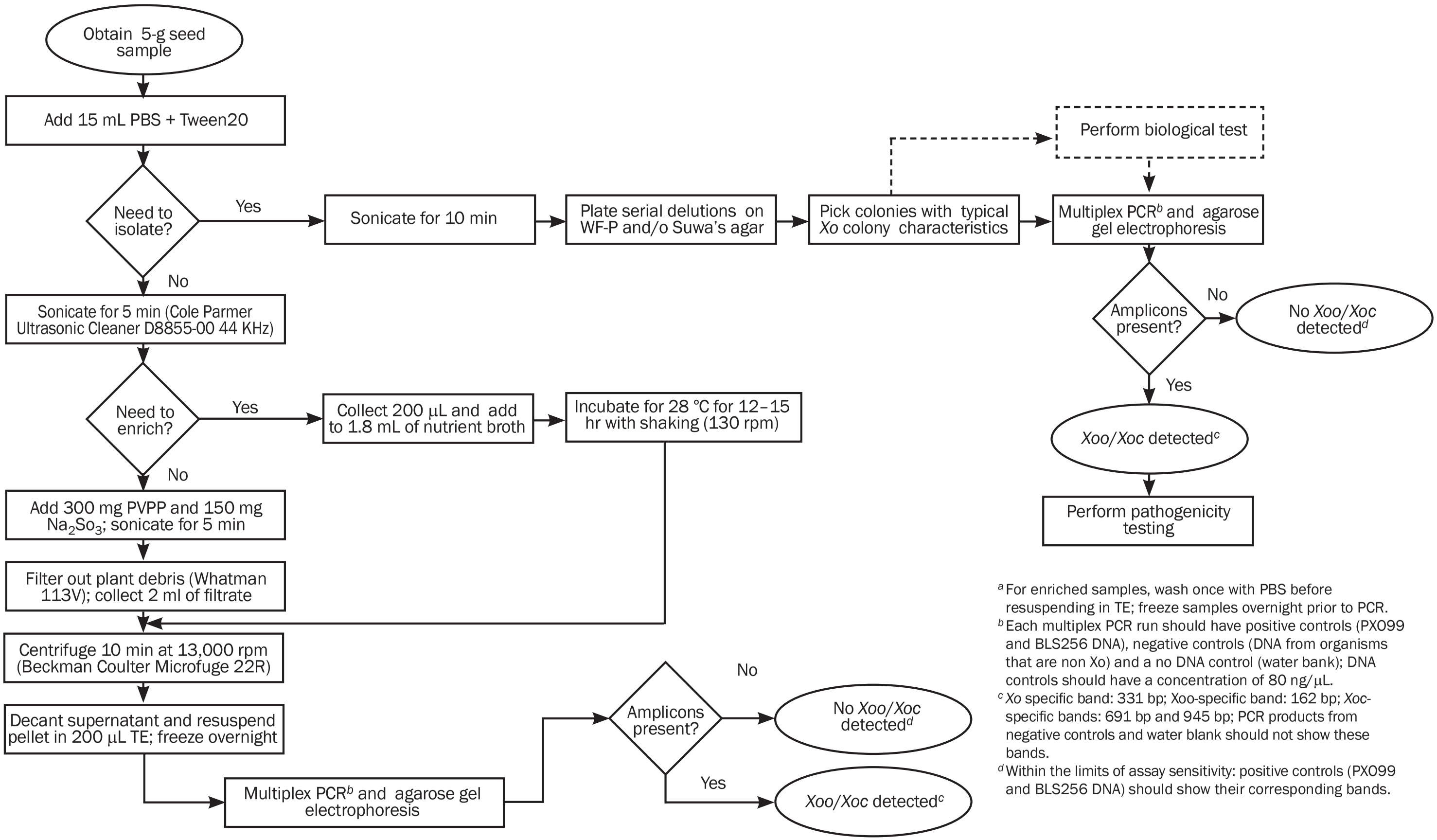


Fig. 4. Gel photos showing PCR amplicons obtained using sonication (SONIC) and vortexing (VOR) for dislodging bacterial cells from seed samples.



[a] For enriched samples, wash once with PBS before resuspending in TE; freeze samples overnight prior to PCR.
[b] Each multiplex PCR run should have positive controls (PXO99 and BLS256 DNA), negative controls (DNA from organisms that are non Xo) and a no DNA control (water bank); DNA controls should have a concentration of 80 ng/µL.
[c] *Xo* specific band: 331 bp; Xoo-specific band: 162 bp; *Xoc*-specific bands: 691 bp and 945 bp; PCR products from negative controls and water blank should not show these bands.
[d] Within the limits of assay sensitivity: positive controls (PXO99 and BLS256 DNA) should show their corresponding bands.

Fig. 5. Harmonized protocol for the detection of *Xo* pathovars from rice seeds.

suspected isolates, confirmation of the identity of isolates using multiplex PCR, and testing for pathogenicity in susceptible plants. The conduct of a training-workshop is part of the overall goal to provide a validated, standard protocol to detect these pathogens from rice seeds for use in quarantine, research, or institutions involved in the global movement of rice seeds.

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Molecular marker-based identification of restorers and maintainers in rice

G.V. Rajendra Krishna, B. Vishnuvardhan Reddy, and M.S.Ramesha

The identification of maintainers and restorers from genetically diverse materials is a prerequisite for developing hybrid rice. Restorers and maintainers are usually identified by evaluating the pollen and spikelet fertility of testcross hybrids. Phenotypic evaluation is a cumbersome, labor-intensive, and time-consuming method. The use of microsatellite markers tightly linked to fertility restorer genes will help in the rapid identification and use of parental lines. A set of 165 breeding lines from IRRI was evaluated for the presence of fertility restorer gene *Rf4* using simple sequence repeat marker RM 6100. Standard maintainers and restorers were used as checks. The entries were classified as maintainers and restorers based on their unique banding patterns compared with those of checks. Molecular data were compared with spikelet fertility data of testcross hybrids evaluated in the field. Of 165 lines evaluated, 72 maintainers and 50 restorers showed one-to-one correspondence with molecular data. The frequency of maintainers identified was 77.55% and 54%, respectively, in breeding lines for salinity, aerobic, and lowland conditions. The highest frequency of restorers was identified in NPT and other breeding lines, 71% and 47%, respectively. By using a single SSR marker (RM 6100), restorers and maintainers could be identified with 74% accuracy. The missmatch in the rest of the cases may be because of different genes involved or a crossover event. Marker-based identification of hybrid parental lines will enhance breeding efficiency and thereby accelerate the development of heterotic hybrids.

Rice (*Oryza sativa* L.) is the staple food for more than half of the world's population. Hybrid rice technology is one of the promising, sustainable, and proven technologies for enhancing rice productivity, with a yield advantage of 15–20% over inbred varieties (Balaji Suresh et al 2012). Rice hybrids occupy more than 50% of the rice area in China and are being adopted in other rice-growing countries (Virmani et al 2003). Two different approaches are now adopted for developing rice hybrids. The first approach is called the three-line system, involving a cytoplasmic male sterile line, a maintainer line, and a restorer line. This is the most popular method worldwide in almost all crops, including rice, in which hybrids have been developed and commercialized. Cytoplasmic male sterility (CMS) is a maternally inherited trait that results in the inability of the plant to produce fertile pollen. Pollen fertility is restored by a nuclear-encoded gene called a fertility restorer (*Rf*) gene. The second approach is called the two-line system, involving environmentally sensitive male sterility. Hybrids of this kind are grown to a limited extent only in China (Sheeba et al 2009).

All commercial rice hybrids grown in India and other south Asian countries and the majority of hybrids grown in China, Vietnam, and elsewhere are based on the three-line system. Plant breeders produce fertile hybrid seeds by crossing female lines that carry male sterilizing cytoplasm (A lines) with a male line that carries the gene for fertility restoration (an R line) in its nucleus. The identification of restorer and maintainer lines is the basic step involved in a hybrid breeding program. Restorers and maintainers are identified by evaluating testcross hybrids involving a CMS line and a pollen parent for pollen and spikelet sterility status. A testcross hybrid with more than 85% pollen and spikelet fertility indicates that the pollen parent used in producing the testcross hybrid is a restorer. If the hybrid has more than 98% of pollen and spikelet sterility, then the male parent is classified as a maintainer. This conventional method of identifying restorers and maintainers among thousands of breeding lines generated in hybrid rice breeding programs requires two seasons to get results and it is labor-intensive in making hand crosses, evaluating testcross hybrids, and generating data on pollen and spikelet sterility. DNA markers, either gene-based or tightly linked to fertility restorer genes, can help in the identification of R and B lines within a week's time without raising the crop. The use of molecular markers linked to *Rf* genes can enhance selection efficiency, save time, and avoid the complications associated with phenotype-based screening. The fertility restorer genes *Rf3* and *Rf4* for wild abortive-type CMS have been mapped on chromosomes 1 and 10, respectively (Yao et al 1997). The role of the *Rf4* locus in fertility restoration and its location on chromosome 10 have been identified by many research groups (Singh et al 2005, Sheeba et al 2009). Simple sequence repeat marker RM6100 has been reported to be linked to *Rf4* (Singh et al 2005). Our study was undertaken to identify the potential restorers and maintainers in 165 breeding lines at the molecular level by using marker RM6100 and also field evaluation of 165 testcross hybrids was done to compare the accuracy of genotypic data with that of phenotypic data.

Materials and methods

In our study, we evaluated a set of 165 breeding lines from the International Rice Research Institute (IRRI) for the presence of fertility restorer gene *Rf4* using SSR marker RM 6100. Of the 165 lines, 44 were aerobic lines, 70 low land irrigated lines, 13 salinity-tolerant lines, 13 Green Super Rice lines, 14 new plant type lines, and 11 INGER lines (Table 1). Testcrosses of all these 165 breeding lines were made with popular male sterile lines such as IR58025A and APMS 6A during kharif 2010 (Wet season: July to October) and all the testcross hybrids (15–20 plants per cross) were evaluated in the field along with the parents during rabi 2011 (dry season: December to April) at the research farm of the Barwale Foundation, Hyderabad, India, following the recommended package of practices.

Total genomic DNA was isolated from young healthy leaves of all 165 breeding lines, including standard restorer checks PRR-78 and KMR-3 and maintainer checks IR58025B and APMS6B by following the method of Dellaporta et al (1983).

Polymerase chain reaction (PCR) was carried out in a BIO-RAD MyCycler Thermal Cycler. PCR was carried out using 25–30 ng of template DNA, 200 μM of dNTPs (Fermentas**,** USA), 5 picomoles of each F and R primer, 0.5 unit of Taq DNA polymerase (Bangalore Genei, India), and 1× PCR reaction buffer (Bangalore Genei, India) in a total volume of 15 μ*L*. The cycling conditions were an initial denaturation at 95 °C for 5 min followed by 30 cycles of PCR amplification under the following parameters: 15 s at 94 °C, 30 s at 55 °C, and 45 s at 72 °C, followed by a final extension at 72 °C for 6 min. Amplified products were separated on 6% denatured polyacrylamide gel using vertical polyacrylamide gels (BIO-RAD, USA) and visualized after silver staining (Panaud et al 1996). The linkage map published by Singh et al (2005) clearly shows that the genomic region controlling the *Rf* trait is located near marker RM6100. Marker RM6100 was very close to the gene at a genetic distance of 1.2 cM. The linkage map of chromosome 10 appears in Figure 1 and the sequence details of marker RM6100 are given in Table 2.

Results

Testcross entries with complete panicle exsertion and more than 80% spikelet fertility were classified as restorers and the testcross progenies with incomplete panicle exsertion were subjected to a pollen study and entries with 98% to 100% pollen sterility were classified as maintainers. The molecular data were compared with spikelet fertility data of testcross hybrids. Out of 165 lines evaluated, 122 (50 restorers and 72 maintainers) showed one-to-one correspondence with the molecular data. Details on the frequency of restorers and maintainers identified appear in Tables 3 and 4.

Discussion

The identification of restorers and maintainers from genetically diverse materials is a prerequisite for developing hybrid rice. Restorers and maintainers are usually identified by evaluating testcross hybrids for pollen and spikelet fertility. Phenotypic

Table 1. International Rice Research Institute (IRRI) breeding materials used in the study.

Type of material	Number of lines
Lowland irrigated lines	70
Aerobic breeding lines	44
New plant type lines (NPT-II)	14
Salinity-tolerant lines	13
Green Super Rice	13
International Network for Genetic Evaluation of Rice (INGER) lines	11
Total	165

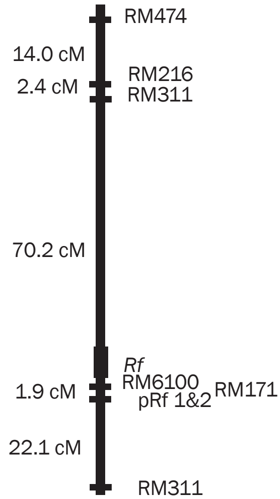

Fig. 1. Linkage map of rice chromosome 10, showing relative distance between markers. Makers are indicated on the right and map distances, based on Kosambi function, are on the left. (Sheeba et al 2005).

Table 2. Primer sequence of the DNA marker used.

Marker type	Marker	Linked *Rf* gene	Primer sequence	Reference
SSR	RM6100	Rf 4	**F**: 5' TCCTCTACCAGTACCGCACC3' **R**: 5'GCTGGATCACAGATCATTGC3'	Singh et al (2005)

Table 3. The frequency of restorers identified in various lines.

Material	Percentage
NPT-II	71
GSR	69
Low land	36
Inger	18
Salinity	15
Aerobic	7

Table 4. The frequency of maintainers identified in various lines.

Material	Percentage
Inger	73
Salinity	62
Aerobic	55
GSR	15

evaluations are a cumbersome, labor-intensive, and time-consuming method. There is a great deal of diversity in the genetics of restoration both among and within species. The diversity in restoration systems extends to the number of restorer genes. In some systems, one or two major restorer loci confer complete restoration. In others, full restoration requires the concerted action of a number of genes, many of which provide only small incremental effects (Schnable and Wise 1998). It was discovered that fertility restoration is controlled by two independent dominant nuclear genes with one stronger in action than the other (Young and Virmani 1984). The use of microsatellite markers tightly linked to fertility restorer genes (*Rf*) will help in the rapid identification and use of parental lines and thereby increase breeding efficiency.

To assess the selection accuracy of RM6100 in marker-aided selection for the trait phenotype, 165 breeding lines were analyzed. Standard restorers PRR-78R and KMR-3 and maintainers IR58025B and APMS6B were used as checks. The lines were classified as restorers and maintainers based on their unique banding patterns in comparison with those of the checks. The maintainer lines and restorer lines produced bands with sizes of approximately 140 bp and 155 bp, respectively (Figure 2). The primer RM6100 showed an overall selection accuracy of 74% with regard to all 165 lines. When various individual lines were analyzed in detail for identifying potential restorers, the highest frequency of restorers was identified in new plant type-II lines (71%) followed by Green Super Rice lines (69%), lowland lines (36%), INGER lines (18%.), salinity lines (15%), and aerobic lines (7%).

When various individual lines were analyzed in detail to identify maintainers, the highest frequency of maintainers was identified in INGER lines (73%), followed by salinity lines (62%), Aerobic lines (55%), and Green Super Rice line (15%). Interestingly, restorer PRR-78R showed a banding pattern different from that of other restorers, with a size of approximately 165 bp (Figure 2). Similar results were reported by Sheeba et al (2009) and primer RM6100 showed 94.9% selection accuracy. According to Sheeba et al (2009), PRR-78R is a special restorer derived from Basmati varieties and, hence, it could have a different restorer allele. In-depth investigation of the novel fertility restoration allele in this restorer line should be carried out to confirm this. Singh et al (2005) already reported the usefulness of this marker in marker-aided selection, with a selection accuracy of 97%. The failure of marker RM6100 in distinguishing the other 43 lines into appropriate restorers and maintainers may be because those lines have a different set of fertility restorer genes.

RM6100 is co-dominant and is capable of discriminating three kinds of genotypes: Rf/Rf, Rf/rf, and rf/rf. Hence, this marker is indeed very useful for identifying the restorers in segregating populations; it can accelerate the breeding of restorer lines and

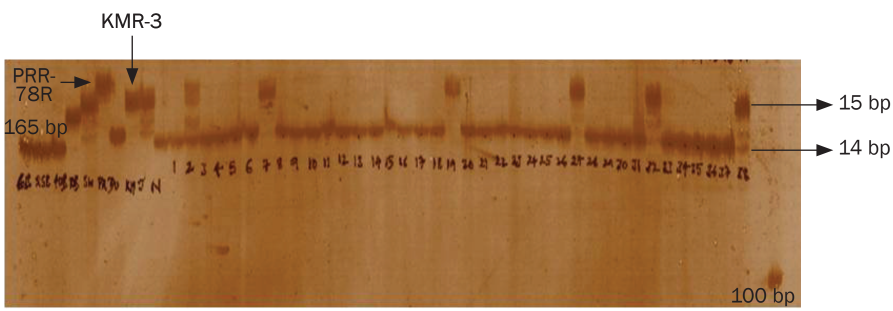

Fig. 2. Evaluation of the presence of fertility restorer gene *Rf4* using SSR marker RM6100 in the lines based on unique banding patterns in comparison with those of standard checks.

can thus enhance efficiency in hybrid rice breeding (Sheeba et al 2009). As marker RM6100 is closely linked to the *Rf* locus, it could be useful in routine screening of germplasm to identify potential restorers. Prediction based on a single marker is 74% accurate and the use of one more marker linked to a fertility restorer gene will be very useful for increasing accuracy. Marker-based identification of hybrid parental lines will be less time consuming and will enhance breeding efficiency and thereby accelerate the development of heterotic hybrids in the near future.

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Pyramiding genes for bacterial blight and blast resistance into an elite basmati rice restorer line (PRR78) through marker-assisted selection

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Bacterial blight (BB) caused by *Xanthomonas oryzae*pv. *oryzae* and blast caused by *Magnaporthe oryzae* are major constraints that limit rice productivity. Marker-assisted backcross breeding was used to incorporate BB resistance genes (*xa13* and *Xa21*) and blast resistance genes (*Piz5* and *Pi54)* into the genetic background of an elite basmati restorer line, PRR78, which resultedin the development of Pusa1601 (PRR78+*xa13*+*Xa21*) and Pusa 1609 (PRR78+*Piz5*+*Pi54*), respectively. Furthermore, in order to combine the genes *xa13, Xa21, Piz5,* and *Pi54* into the genetic background of PRR78, Pusa 1601 and Pusa 1609 were intercrossed to develop Pusa 1790, and foreground marker-verified true F_1 s plants were selfed to generate an F_2 population of 1,509 individuals. Stringent phenotypic selection was used to identify 400 plants resembling PRR78, which underwent foreground analysis. A total of three, five, and 16 plants homozygous for four, three, and two genes in different combinations, respectively, were identified and advanced to F_3. In F_3, evaluation for agronomic performance, disease reactions under artificial inoculations, and grain and cooking quality traits was performed, leading to the development of improved lines of PRR78. These lines, designated with the prefix Pusa 1790, carry genes *xa13*+*Xa21* for BB resistance and *Piz5*+*Pi54* for blast resistance. Hybrids using improved restorer lines have been generated to evaluate their heterotic potential.

Keywords: bacterial blight, blast, gene pyramiding, hybrid rice, molecular markers, marker-assisted selection

Pusa RH10 is a superfine-grain aromatic rice hybrid combining high yield and short duration and thus very high per day productivity (Siddiq et al 2009). Despite being very popular, this hybrid is highly susceptible to two of the most dreaded diseases of rice, bacterial blight (BB) caused by *Xanthomonas oryzae* and blast caused by *Magnaporthe oryzae.* Presently, BB and blast diseases are managed mainly through the application of fungicide/antibiotics, which is costly as well as unsustainable. Despite the adoption of these control measures, under epidemic conditions, BB causes yield losses up to 70% (Mew and Vera Cruz 2001). Likewise, blast disease causes upto a

50% yield loss in rice globally (Scardaci et al 1997). The development of resistant cultivars is considered to be the most effective method to counteract the pathogen. However, cultivars undergo rapid breakdown in their resistance mainly caused by the emergence of new pathotypes, due to the high instability in the genome of the pathogen (Dean et al 2005). Therefore, bringing together multiple genes conferring resistance to more than one pathotype into one genetic background is necessary for durable resistance.

To date, 39 BB resistance genes and 100 blast resistance genes have been identified, out of which 9 BB and 19 blast resistance genes have been cloned. The availability of such a large number of mapped resistance genes makes it possible to integrate two or more of them into a genotype, called "gene pyramiding" (Bonman et al 1992). This approach is considered a powerful tool to build up broad and durable resistance in a variety (Hittalmani et al 2000, Dangl and Jones 2001, Michelmore 2003, Werner et al 2005). The use of molecular markers is essential in gene pyramiding, which aids in tracking specific loci in segregating populations, which is a substitution for phenotypic screening (Francia et al 2005).

Marker-assisted selection (MAS) offers a simple, more efficient, and accurate way of breeding that is handy in breeding for disease resistance compared with selection only based on phenotype. A large repertoire of molecular markers is available in rice, which is quite valuable for marker-assisted selection. Marker-assisted pyramiding of major genes/QTLs has helped in tackling susceptibility for major diseases and insects such as bacterial blight (Huang et al 1997, Singh et al 2001, Zhang et al 2006, Liu and Anderson 2003, Joseph et al 2004,Gopalakrishnan et al 2008, Sundaram et al 2008, Basavaraj et al 2010, Hari et al 2011, Bhatia et al 2011, Suh et al 2011), blast (Hittalmani et al 2000, Zhou et al 2011, Singh et al 2011, Singh et al 2012a,b), sheath blight (Wang et al 2011, Singh et al 2012b), brown planthopper (Suh et al 2011, Hu et al 2012), and gall midge (Katiyar et al 2001).

Considering the economic impact of Pusa RH10 and concerns about its susceptibility to BB and blast, the incorporation of multiple BB and blast resistance genes into its restorer line, PRR78, was perceived as an essential requirement. Since Pusa RH10 is a superfine-grain aromatic rice hybrid, retention of grain quality traits in the parental line and the hybrid is of utmost importance during improvement of parental lines for these diseases. With this background, our investigation was undertaken with the objective of pyramiding genes for BB and blast resistance into the background of PRR78 without losing its heterotic potential with Pusa 6A, the female parent of the hybrid Pusa RH10, and its grain and cooking quality.

Materials and methods

Plant materials and the development of improved lines

PRR78, the restorer line of the hybrid Pusa RH10, was used as the recurrent parent, while Improved Pusa Basmati 1 (IPB1, carrying BB resistance genes *xa13+Xa21*), Tetep (carrying blast resistance gene *Pi54*), and C101A51 (carrying blast resistance gene *Piz5*) were used as the donor parents for the BB and blast resistance genes, respectively.

Marker-assisted backcross breeding

Three independent crossing programs were started for the development of BB- and blast-resistant lines using PRR78 as the female and three donor parents (IPB1, C101A51, and Tetep) as males, and the resultant crosses were designated as Pusa 1601, Pusa 1602, and Pusa 1603, respectively. In each case, true F_1s plants were identified based on the respective gene-based/linked markers and were backcrossed with PRR78 to produce BC_1F_1 seeds. In BC_1F_1, the plants heterozygous for the target locus underwent stringent phenotypic selection for identifying the plants possessing maximum similarity to the recurrent parent phenotype. The selected plants were used to generate BC_2F_1 seeds. For the development of Pusa1601, BC_2F_1 were selfed to generate a BC_2F_2 population, and the desirable plants were selfed through the pedigree method of selection upto the BC_2F_5 generation. However, BC_2F_1 plants possessing desirable alleles and with maximum recovery of the recurrent parent phenome (RPP) of Pusa 1602 and Pusa1603 series were intercrossed to generate Pusa 1609 (*Piz5* and *Pi54*). The plants homozygous for both genes (*Piz5* and *Pi54*) were identified in the F_2 generation and advanced upto the F_4 generation through pedigree selection. The elite lines of Pusa 1601 (*xa13+Xa21* and Pusa1609 (*Piz5* and *Pi54*) were intercrossed to develop a BB- and blast-resistant restorer line, which was designated as Pusa 1790 (carrying *xa13+Xa21* and *Piz5+Pi54*). The schematic representation of marker-assisted backcross breeding (MABB) appears in Figure 1.

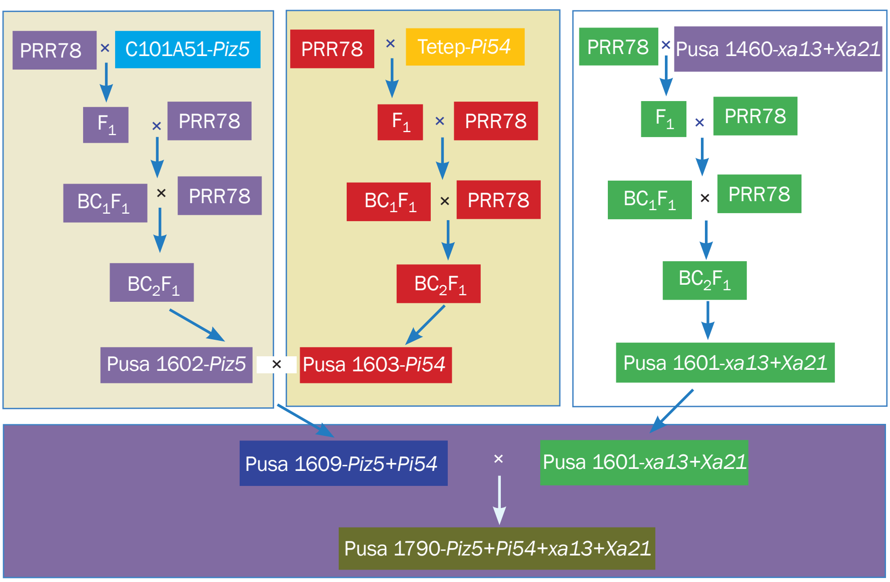

Fig. 1. Breeding scheme for the development of Pusa 1790 through marker-assisted introgression of BB and blast resistance genes into the genetic background of PRR78.

Molecular marker analysis

Foreground selection. Gene-based markers *xa13*-prom (Singh et al 2011) and pTA248 (Ronald et al 1992), were used for BB resistance genes*xa13* and *Xa21*, respectively. The SSR marker RM206 linked (0.6cM) to the blast resistance gene *Pi54* (Sharma et al 2005) and another SSR marker, AP5930, linked (0.1cM) to *Piz5* (Fjellstrom et al 2006), were used for foreground selection in segregating generations. Since the recurrent parent is a restorer line, foreground selection for fertility restorer gene *Rf1* was essential, which was done using *Rf1* gene-linked marker RM6100 (Singh et al 2011). The details of the genes, markers, and genetic materials used in the study are presented in Table 1.

Background selection. To help identify plants with a maximum recurrent parent genome, a set of 435 SSR markers spanning the 12 chromosomes was used to identify genome-wide polymorphic SSR markers in thee parental combinations, namely, PRR78 with IPB1, C101A51, and Tetep. These polymorphic SSR markers were used to estimate the RPG recovery in the backcross-derived line and, with the help of Graphical Genotypes (GGT) Version 2.0 (Van Berloo 1999) software, the genomic contribution of parents in selected elite lines was analyzed.

DNA extraction and PCR amplification

Total genomic DNA was extracted using the micro-extraction protocol of Prabhu et al (1998). Polymerase chain reaction was performed in a Thermal Cycler (G Storm, UK) using a total volume of 10 mL reaction containing 30 ng of template DNA, 5 pmole of each primer (synthesized from Sigma Tec., Bangalore), 1.5 mM of $MgCl_2$, 0.2 mM of dNTPs (MBI Fermentas, Vilnius, Lithuania), and 0.5U of *Taq* polymerase (Bangalore Genei, Bangalore). The PCR condition was with one cycle of denaturation at 95°C for 5 min followed by 35 cycles at 95°C for 30s, 55°C for 30s, and 72°C for 1 min, with a final extension of 72°C for 7 minutes. The amplified products were resolved in 3.5% Metaphor™ gel (Lonza, Rockland, ME, USA) containing 0.1 µg/mL of ethidium bromide (Amresco, USA) and documented in the Gel documentation system (Biorad, USA).

Screening for BB resistance

The backcross-derived lines carrying BB resistance genes were inoculated with a bacterial suspension of 10^9 cells/mL at maximum tillering stage using the most virulent

Table 1. The markers used for foreground selection.[a]

Gene	Recurrent parent	Donor parent	Marker	LG	MD (cM)	Reference
xa13	PRR78	IPB-1	xa13-prom	8	GB	Singh et al (2011)
Xa21	PRR78	IPB-1	pTA248	11	GB	Ronald et al (1992)
Piz5	PRR78	C101A51	AP5930	6	0.10	Fjellstrom et al (2006)
Pi54	PRR78	Tetep	RM206	11	0.60	Sharma et al (2005)
Rf1	PRR78	–	RM6100	10	6.50	Singh et al (2011)

[a] IPB1 (Improved Pusa Basmati 1); LG = linkage group; MD = marker distance; GB = gene-based.

Kaul isolates of *Xanthomonas oryzae* pv. *oryzae* (Joseph et al 2004). The leaf clipping method of Kauffman et al (1973) was used to inoculate five young leaves in each plant and the disease reaction was recorded after 21 days. Plants exhibiting average lesion length of up to 6 cm were considered as resistant and those with lesion lengths of >6 cm were scored as susceptible.

Screening for blast resistance

The seedlings of selected advanced families were grown in plastic trays, and 21-day-old seedlings were inoculated with the four most virulent blast isolates collected from the basmati rice-growing regions of northern India as reported by Singh et al (2012a). The inocula were prepared as per the procedure of Bonman et al (1986) and the plants in each tray were sprayed with 50 mL of inoculum with a conidial density of 5×10^4 per mL and kept for 24 h at 25°C in a dew chamber. Subsequently, these plants were maintained for 1 wk at 25°C in the dew chamber before scoring. Seven days after inoculation, the plants from the families were scored for blast resistance on a 0–5 scale as per Bonman et al (1986). The plants exhibiting a reaction score of 0–3 were considered as resistant while those showing a score of 4–5 were considered as susceptible.

Evaluation of agronomic performance and grain quality analysis

The advanced backcross-derived lines along with parental lines were planted at 15 × 15 cm spacing in a randomized complete block design with three replications and evaluated for agronomic traits during kharif 2012 at the experimental farm of the Division of Genetics, IARI, New Delhi, India. Data for five plants were taken to determine the following agronomic traits: plant height (PH), number of tillers per plant (NT), panicle length (PL), filled grains per panicle (FG/P), spikelet fertility (SF), 1,000-grain weight (GW), and yield per plant (Y/P). Grain quality traits were analyzed according to grain size, kernel length before cooking (KLBC), kernel length after cooking (KLAC), kernel breadth before cooking (KBBC), kernel breadth after cooking (KBAC), length/breadth ratio (L/B), elongation ratio (ER), alkali spreading value (ASV), and aroma as described in Basavaraj et al (2010).

Results

Marker-assisted backcross breeding comprising foreground and background selection was employed to develop BB- and blast-resistant restorer lines in the genetic background of basmati rice restorer line PRR78. The improved versions of PRR78, namely, Pusa1601 (carrying BB resistance genes *xa13* and *Xa21*), Pusa 1602 (carrying blast resistance gene *Piz5*), Pusa 1603 (carrying blast resistance gene *Pi54*), Pusa 1609 (carrying two blast resistance genes, *Piz5* and *Pi54*), and Pusa1790 (carrying two BB resistance genes, *xa13* and *Xa21,* and two blast resistance genes, *Piz5* and *Pi54*), were developed and the significant findings are presented as follows.

The development of Pusa 1601 (PRR78+*xa13*+*Xa21*)

Pusa 1601 was developed by crossing PRR78 with IPB 1 as the donor for BB resistance genes, *xa13* and *Xa21* in our lab earlier (Basavaraj et al 2010). The BC_2F_5 plants of the backcross series were highly resistant to bacterial blight disease, showing lesion length of <2.0 cM. The agronomic performance and grain and cooking quality attributes of Pusa 1601 lines in both backcross series were similar to those of the respective recurrent parents. However, some of the selections in both populations were superior to the recurrent parents. Improved lines of PRR78 showed a yield advantage up to 5.23%, respectively, under disease-free conditions, which could be due to the presence of donor parent segments with a positive effect in other genomic regions. Pusa 1601 (PRR78+*xa13*+*Xa21*) lines were crossed with CMS line Pusa6A, the female parent of the original hybrid Pusa RH10, to generate a new set of hybrids. The newly developed hybrids showed heterosis similar to that of Pusa RH10 with resistance to bacterial blight.

The development of Pusa 1602 (PRR78+*Piz5*) and Pusa 1603 (PRR78+*Pi54*)

In an earlier study in our lab, two major broad-spectrum genes, namely, *Piz5* and *Pi54,* conferring resistance to blast disease were transferred into PRR78 from C101A51 and Tetep, respectively, in two separate backcross series and named Pusa1602 and Pusa 1603, respectively (Singh et al 2012a). Marker-assisted foreground and background selection was also integrated with phenotypic selection for agronomic and grain and cooking quality traits, to accelerate recovery of the recurrent parent genome and phenome. The best BC_2F_1 plants from each backcross breeding program were selfed to produce F_2 populations and MAS was used to identify plants homozygous for each gene; the selected plants were advanced to the BC_2F_5 generation through pedigree selection to develop improved versions of PRR78 with blast resistance. Based on the background analysis using a genome-wide SSR marker,Pusa 1602-06-30-1-51 showed 89.01% and Pusa 1603-06-10-2-12 showed 87.88% recurrent parent genome recovery (RPG). The disease reaction of improved lines and their recurrent and donor parents was variable under artificial inoculation with different isolates (Fig. 2A and 2B). The hybrids produced by crossing Pusa 6A with improved lines of PRR78 with blast resistance were found to be on a par with hybrid Pusa RH10 in yield and grain and cooking quality traits, with an advantage of blast resistance.

The development of Pusa 1609 (PRR78+*Piz5*+*Pi54*)

The pyramiding of disease resistance genes into an elite genetic background is an effective approach for managing important diseases in crops. In yet another study carried out in our lab earlier (Singh et al 2013), amarker-assisted simultaneous but stepwise backcross breeding (MASS-BB) approach was used for pyramiding two blast resistance genes from two different donors into PRR78to develop Pusa 1609 in our lab. Improved versions of Pusa RH10 developed by crossing Pusa6A, the female parent of Pusa RH10, with different lines of Pusa 1609 (PRR78+*Piz5*+*Pi54*) performed on a par with the original Pusa RH10 and showed resistance to blast disease both under artificial screening and at hot-spot locations.

The development of Pusa 1790 (PRR78+*xa13*+*Xa21*+*Piz5*+*Pi54*)

The near-isogenic lines of PRR78 (Pusa1601 and Pusa 1609) were intercrossed to develop Pusa 1790. Gene-based markers were used for confirming the hybridity and

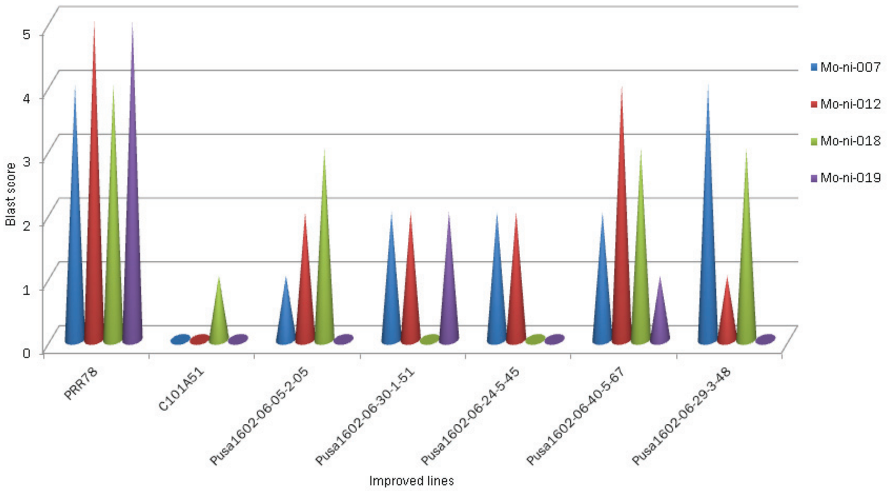

Fig. 2a. Graphical representation of recurrent parent (PRR78), donor parent (C101A51), and near-isogenic lines of PRR78 (Pusa 1602) carrying gene *Piz5* in artificial inoculation condition. Different color bars represent the disease reaction score for four different virulent isolates collected from different location of Basmati-growing regions of India.

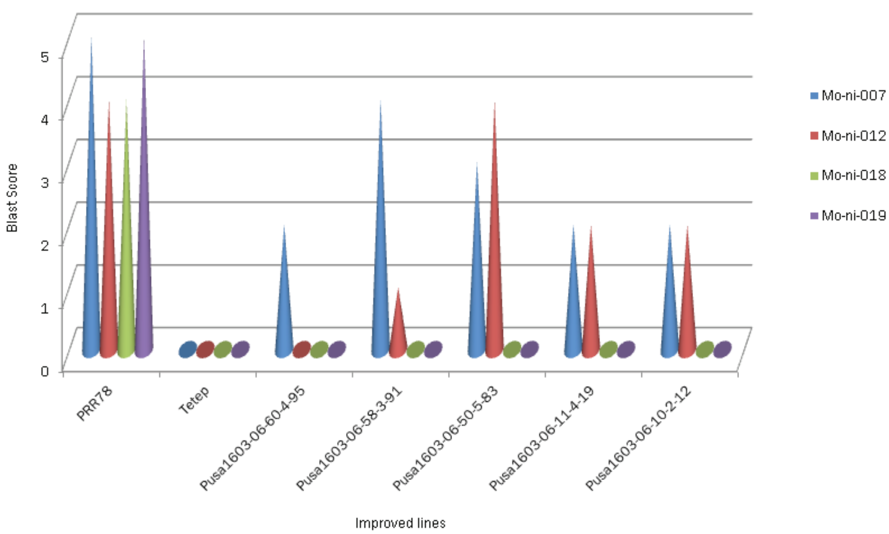

Fig. 2b. Graphical representation of recurrent parent (PRR78), donor parent (Tetep), and near-isogenic lines of PRR78 (Pusa 1603) carrying gene *Pi54* in artificial inoculation condition. Different color bars represent the disease reaction score for four different virulent isolates collected from different location of Basmati-growing regions of India.

true F_1 plants were selfed to generate an F_2 population of 1,509 individuals. On the basis of phenotypic selection for agro-morphological characters in the recurrent parent, 400 plants were selected and subjected to foreground analysis. Marker-assisted foreground selection was carried out for identifying plants carrying a combination of two, three, and four genes using the respective markers, as mentioned above. A total of three, seven, and 16 plants homozygous for four, three, and two genes in different combinations, respectively, were identified and advanced to the F_5 generation (Table 2). In F_5, phenotypic selection for agronomic performance, disease reactions under artificial inoculation, and grain and cooking quality traits was performed. These promising lines are now being used in generating testcross hybrids to evaluate their heterotic potential.

The development of improved Pusa RH10

Several testcross combinationswere generated using the improved lines of Pusa 1601 and Pusa 1609 with Pusa6A (CMS line of Pusa RH10). The promising hybrid combinationsare being multiplied on a large scale for multilocation testing. Only one BB-resistant hybrid (Pusa RH 10-01-03) was found to be on a par with the original Pusa RH10. However, blast-resistant hybrids showed a yield advantage of 23.53% in Pusa RH 10-09-14 to 37.06% in Pusa RH 10-09-16 in comparison with the original Pusa RH10 (Table 3).

Table 2. Promising lines of Pusa 1790 with different gene combinations and superior grain quality.

Plant number	Generation	Gene status (gene-based/linked markers)			
		xa13 (xa13-prom)	*Xa21* (pTA248)	*Piz5* (AP5930)	*Pi54* (RM206)
Pusa 1790-10-638	F_5	++	++	++	++
Pusa 1790-10-651	F_5	++	++	++	++
Pusa 1790-10-705	F_5	++	++	++	++
Pusa 1790-10-539	F_5	++	–	++	–
Pusa 1790-10-646	F_5	++	–	–	++

Table 3. Yield advantage of BB- and blast-resistant hybrids.

Hybrids	Details	Yield in (kg) plot of 3.2 m^2	% advantage over Pusa RH 10
Pusa RH 10-01-03	Pusa6A/Pusa 1601-5	3.10	2.94
Pusa RH 10-09-14	Pusa6A/Pusa 1609-6	3.80	23.53
Pusa RH 10-09-15	Pusa6A/Pusa 1609-3	3.96	28.24
Pusa RH 10-09-16	Pusa6A/Pusa 1609-D	4.26	37.06
Imp. restorer line	Pusa 1601 (R)	2.60	–
Imp. restorer line	Pusa 1609 (R)	2.30	–
Original restorer line	PRR78	2.20	–
Original hybrid	Pusa RH10	3.00	–

Conclusions

Our study was undertaken with a view to improve basmati quality restorer line PRR78, the male parent of a superfine-grain aromatic rice hybrid, Pusa RH10, for resistance to BB and blast diseases, with an ultimate goal to develop rice hybrids with built-in resistance to BB and blast. To achieve this goal, marker-assisted foreground selection was successfully combined with phenotypic selection for yield and its components and grain and cooking quality traits, followed by background analysis to develop an improved version of PRR78 with resistance to BB and blast. The use of MAS with robust STMS markers has been very effective in improving PRR78. The improved versions of PRR78, namely, Pusa 1601 (PRR78+*xa13*+*Xa21*), Pusa 1602 (PRR78+*Piz5*), Pusa 1603 (PRR78+*Pi54*), Pusa 1609 (PRR78+*Piz5*+*Pi54*), and Pusa 1790 (PRR78+*xa13*+*Xa21*+*Piz5*+*Pi54*) carrying BB and blast resistance genes in different combinations were either on a par with or superior to recurrent parent PRR78 in agronomic performance and grain and cooking quality traits, with an added advantage of BB and blast resistance. The improved lines Pusa 1601 and Pusa 1609 were crossed with Pusa6A, and the resulting hybrids were either on a par with or better than Pusa RH10 in yield. The newly developed parental lines and hybrids can be used to replace Pusa RH10, after required testing. Commercial cultivation of BB- and blast-resistant varieties and hybrids will reduce the cost in managing these diseases, thereby increasing the profitability of farmers.In the future, the development of high-throughput markers such as single nucleotide polymorphisms (Gopala Krishnan et al 2012) and high-throughput genotyping facilities (Henry et al 2012) will enable plant breeders to use MAS to expedite the process of improving parental lines and variety development.

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Notes

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Rice hybrids suitable for dry direct seeding in India

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Dry direct seeding is an emerging conservation agriculture technology for sustainable rice production in rice-based cropping systems. A reduced cost of cultivation through savings of water, labor, and energy; improved soil health for better system productivity; and enhanced profitability are the major drivers of direct-seeded rice (DSR) technology. Efficient and timely weed control through better management and appropriate cultivar choice are crucial for the success of DSR. Quick germination, early seedling vigor, better crop establishment, and greater genetic plasticity to adverse conditions make hybrids more suitable for DSR.

Over a period of three years (2009-11) of the CSISA project, 129 hybrids and 134 inbreds of early, medium-early, and medium-maturity groups were evaluated under machine-sown dry direct-seeded conditions at three to five locations in India. In general, the hybrids had a faster rate of germination, higher seedling vigor, better crop establishment, faster canopy coverage, and higher grain yield than the inbreds. Standard heterosis for grain yield ranged from 21% to 30% in early, 18% to 32% in medium-early, and 10% to 13% in medium-maturity hybrids. Based on multilocation and multiyear data, the most promising hybrids identified are US 323, PA 6129, NK 6303, RH 1531, MRP 5402, and Indam 200-028. Hybrids also performed better under zero-till conditions. A few hybrids (JKRH 3333, MRP 5402, and PAC 8512) were tolerant of zinc and iron deficiency under DSR conditions.

Dry direct-seeded rice (DSR) under machine-sown conditions is a conservation agriculture-based technology that helps in increasing the profitability of rice-based cropping systems as a whole by reducing the use of the ever-decreasing availability of labor, water, and other inputs. In the long run, reduced tillage with and without crop residue incorporation followed by crop rotation will help in improving soil health and thereby increasing the productivity and profitability of rice-based cropping systems.

The major drivers of DSR technology are (1) the acute shortage of labor; (2) the availability of large-scale laser-leveling machines that help with better crop establishment and efficient water management to save 10–20% water without any yield penalty; (3) the availability of better weed management techniques, that is, effective pre- and postemergence herbicides; (4) the availability of multicrop direct-seeding machines for precise seeding and fertilizer placement; (5) innovative farmers, proactive cooperatives, and NGOs to popularize the technology; (6) very good private-public partnership; and (7) no yield penalty in rice and increased yield of wheat, resulting in higher system productivity in the rice-wheat cropping system of India.

Direct seeding is a viable alternative to puddled transplanting to overcome the problem of labor and water shortage. The cumulative area under dry mechanized DSR in India during the wet season of 2012 surpassed 0.1 million acres. Large-scale adoption of DSR is possible but prioritizing resources and public-private partnership (PPP) hold the key. Crop establishment determines the success of DSR, for which precise leveling (laser leveling), a quality multicrop planter (inclined seed-metering system), and trained tractor operators are important. Depth of seeding should be manipulated according to soil type, establishment method, and moisture amount.

Pre- and postemergence herbicide application is a must for effective weed management but the choice of herbicides should be as per the dominant weed flora. Incidence of foot rot and false smut is remarkably lower in DSR. Positive effects occur on the yield of succeeding upland crops. DSR may be helpful in recharging the groundwater table. Water savings in DSR vary across management practices, soil types, etc., but optimization of water savings has to be worked out in a way so as to avoid any yield penalty due to water stress. Tailoring varieties to DSR should form the breeding strategy for further productivity gains in DSR. Hence, an attempt has been made to identify hybrids, varieties, and breeding lines suitable for machine-sown dry direct-seeded conditions through multilocation trials over the years.

Multilocation evaluation of hybrids and inbreds under DSR conditions

Under the CSISA project, multilocation evaluation of varieties/hybrids suitable for DSR conditions were conducted through a mini-network consisting of four centers: Punjab Agricultural University (PAU), Ludhiana; Central Soil Salinity Research Institute (CSSRI), Karnal; Govinda Ballaba Pant University of Agriculture and Technology (GBPUAT), Pantnagar; and the Indian Council of Agricultural Research (ICAR) Complex for the Eastern Region, Patna, representing a typical rice-wheat cropping system of the Indo-Gangetic Plains, and Barwale Foundation, Hyderabad, representing the rice-rice cropping system of southern India. Partners from the public and private sector were asked to nominate varieties/hybrids for trials. The materials received from different places were categorized into three maturity groups for trials: early (115–120 days), medium-early (121–130 days), and medium (>130 days).

Based on randomization and the layout of the field, the entire field was marked with lime powder to demarcate the exact length of the plot. The tractor-drawn limit plot seed drill can drill seed and fertilizer through eight tines each spaced at a distance of 20 cm. The motorized rotating brass plate will regulate the seed and fertilizer flow into the tubes. Sowing depth was adjusted to 2 cm and plot size had 1.6-m width and 4–6-m length. Based on the plot size, seed rate per plot (at 20 kg/ha) and fertilizer dose (based on the recommended basal dose for different places) per plot were calculated and used for drilling. Experiments were conducted in an alpha lattice design with three replications. After machine sowing, the plots were irrigated and preemergent application of pendimethalin at 1 kg a.i./ha was made the next day when sufficient moisture was found on the surface of the soil. Postemergent application of bispyribac sodium at 25 g a.i./ha was made at 28 days after sowing. Irrigation frequency was monitored through tension-meter readings at 15-cm depth. Starting from sowing to the panicle initiation stage, a tensiometer reading of 20 kPa was used as a minimum threshold for re-irrigating the field. From PI to 15 days after flowering, near-saturation conditions were maintained. Need-based plant protection measures were used to control insect pests and diseases. In all, 263 entries comprising 129 hybrids and 134 inbreds were evaluated over 3 years. In each of the 3 years, the entries were scored for emergence, initial establishment, crop stand, early-stage seedling vigor, followed by good plant-type traits, tillering ability, desirable grain type and lodging tolerance, other yield-contributing traits, and net plot grain yield.

In the wet season of 2009, trials were conducted at three places: PAU, Kapurthala; CSSRI, Karnal; and Barwale Foundation, Hyderabad. In the early trial, 44 inbreds and 16 hybrids were evaluated (Table 1). Based on the mean yield over three locations, the top two entries were the hybrids PA6129 and P09-023, which recorded a yield advantage of 62% and 59%, respectively, over the check Govind (Table 2). Variety Pant Dhan-16 and breeding line IR83927-B-B-278-CRA-1-1-1 also performed well, with 42% and 23% increased yield, respectively, over the check. In the medium-early trial (Table 1), 35 entries, including 21 hybrids and 14 inbreds, were tested. Based on the mean yield advantage over the best check (PR 115), the promising hybrids identified

Table 1. Multilocation evaluation of entries under mechanized dry DSR.

Trial	No. of entries tested			Location
	Hybrids	Inbreds	Total	
Wet season 2009				
Early	16	44	60	Kapurthala
Medium-early	21	14	35	Karnal
Total	37	58	95	Hyderabad
Wet season 2010				
Early	12	24	36	Ludhiana
Medium-early	15	1	16	Karnal
Medium	11	13	24	Hyderabad
Total	38	38	76	Pantnagar Patna
Wet season 2011				
Early	19	5	24	Ludhiana
Medium-early	18	14	32	Karnal
Medium	17	19	36	Hyderabad
Total	54	38	92	Pantnagar Patna
Grand total	**129**	**134**	**263**	

Table 2. Promising entries identified with early duration (2009).

Entry	Yield[a] (kg/ha)			Mean yield (kg/ha)	% Yield advantage	Nominating agency
	HYD	LUD	KNL			
PA 6129	5,551	9,533	7,813	7,892	62	Bayer CropScience Ltd.
P09-023	5,436	10,811	6,994	7,747	59	Pioneer Company Ltd.
Pant Dhan-16	4,959	8,263	6,845	6,905	42	GBPUAT, Pantnagar
US 310	5,326	4,911	8,941	6,526	34	US Agri Seeds Ltd.
IR83927-B-B-278-CRA-1-1-1	3,698	7,411	6,101	5,992	23	IRRI
Govind (check)	2,103	6,985	4,613	4,875	—	Check

[a]HYD = Hyderabad, LUD = Ludhiana, KNL = Karnal.

Table 3. Promising entries identified with medium-early duration (2009).

Entry	Yield[a] (kg/ha)			Mean yield (kg/ha)	% Yield advantage	Nominating agency
	HYD	LUD	KNL			
NK 6320	6,101	9,870	7,292	7,754	28	Syngenta India Ltd.
NK 6303	6,157	9,256	6,473	7,295	20	Syngenta India Ltd.
GK 5003	5,209	10,482	5,357	7,016	16	Ganga Kaveri Ltd.
NK 6754	4,019	10,501	6,399	6,973	15	Syngenta India Ltd.
PR 115 (check)	3,482	9,137	5,580	6,067	—	Check

[a]HYD = Hyderabad, LUD = Ludhiana, KNL = Karnal.

were NK 6320 (28%), followed by NK 6303 (20%), GK 5003 (16%), and NK 6754 (15%). Details are given in Table 3.

In 2010, out of 76 entries tested, 36, 16, and 24 belonged to early, medium-early, and medium-duration groups, respectively. Even though all the trials were conducted at Hyderabad, Ludhiana, Karnal, Pantnagar, and Patna, mean yield for Pantnagar and Patna in the early and medium trials and for Pantnagar in the medium-early trial was less than 4 t/ha and hence the data from these locations were not included in the analysis. In the early trial, 12 hybrids and 24 inbreds were tested (Table 1). Based on the mean yield across four locations, the top three entries were hybrid US 323, followed by JKRH 2007 and RH 257, which respectively recorded a 48%, 39%, and 34% yield advantage over the check Govind. The two inbred entries (IR83927-B-B-278-CRA-1-1-1 and Pant Dhan-16) were found promising, with a 28% yield advantage over the check Govind (Table 4). In the medium-early trial, 15 hybrids and an inbred check were tested. The top three promising hybrids identified were NK 6303, followed by NK 6754 and RH 1531, with a 61%, 59%, and 56% yield advantage, respectively, over the check IR64. The mean yield of the promising entries ranged from 7,520 to 8,274 kg/ha (Table 5).

In the medium-maturity trial, 13 inbreds and 11 hybrids were tested. The mean yield of the promising entries ranged from 5,806 to 6,675 kg/ha. The top three entries were hybrid MRP 5403, followed by PAC 832 and Indam 200-028, which recorded

Table 4. Promising entries identified with early duration (2010).

Entry	Yield[a] (kg/ha)				Mean yield (kg/ha)	% Yield advantage over check	Nominating agency
	HYD	LUD	KNL	PTN			
US 323	7,898	6,845	7,875	4,391	6,753	48	US Agri Seeds Ltd.
JKRH 2007	6,556	6,133	8,081	4,503	6,318	39	JK Seeds Ltd.
RH 257	6,722	7,290	6,188	4,151	6,088	34	Dev. Gen. Ltd.
IR83927-B-B-278-CRA-1-1-1	4,660	6,997	6,576	5,145	5,845	28	IRRI
Pant Dhan 16	5,019	7,210	6,148	4,883	5,815	28	GBPUAT, Pantnagar
Govind (check)	3,918	4,013	5,803	4,479	4,553	0	

[a]HYD = Hyderabad, LUD = Ludhiana, KNL = Karnal, PTN = Pantnagar.

Table 5. Promising entries identified in medium-early group (2010).

Entry	Yield[a] (kg/ha)			Mean yield (kg/ha)	% Yield advantage	Nominating agency
	HYD	LUD	KNL			
NK 6303	6,666	9,289	8,865	8,274	61	Syngenta India. Ltd.
NK 6754	8,871	7,571	8,028	8,156	59	Syngenta India Ltd
RH 1531	7,755	7,697	8,509	7,987	56	Dev. Gen. Ltd.
PAC 837	7,776	7,745	7,524	7,682	50	Advanta India Ltd.
US 317	8,806	5,995	7,761	7,520	47	US Agri Seeds Ltd.
IR64 (check)	3,884	5,102	6,396	5,127	—	

[a]HYD = Hyderabad, LUD = Ludhiana, KNL = Karnal.

Table 6. Promising entries identified with medium maturity (2010).

Entry	Grain yield[a] (kg/ha)			Mean yield (kg/ha)	% Yield advantage	Nominating agency
	HYD	LUD	KNL			
MRP 5403	4,794	7,578	7,653	6,675	15.2	MAHYCO Ltd.
PAC 832	5,046	7,285	7,348	6,560	13.2	Advanta India Ltd.
Indam 200-028	5,742	7,246	6,430	6,473	11.7	Indo American Hybrids Ltd.
MRP 5402	6,056	6,747	6,237	6,346	9.5	MAHYCO Ltd.
PAU 3879-87-4-1	3,459	7,348	6,610	5,806	0.15	PAU, Ludhiana
JKRH 3333	6,449	4,888	5,856	5,731	—	JK Seeds Ltd.
NDR 359	4,479	6,504	6,408	5,797	—	Check

[a]HYD = Hyderabad, LUD = Ludhiana, KNL = Karnal.

a mean yield advantage of 15%, 13%, and 12%, respectively, over the best check, NDR 359 (5,797 kg/ha). In the same trial, one breeding line (PAU 3879-87-4-1) having bacterial leaf blight resistance from PAU, Ludhiana, and one medium slender grain hybrid from JK Seeds Ltd. (JKRH 3333) recorded yield on a par with that of the check (Table 6).

In the wet season of 2011, 92 entries comprising 54 hybrids and 38 inbreds were evaluated at five locations. In the early trial, 19 hybrids and 5 inbreds were tested; data from Ludhiana and Pantnagar were not considered because of the location mean yield of below 4 t/ha. Out of the top five promising entries identified, the top three were hybrid US 323 with a mean yield of 6,872 kg/ha, followed by RH 257 (6,765 kg/ha) and MRP 5901 (6,673 kg/ha). These hybrids recorded a yield advantage of 37%, 35%, and 33%, respectively, over the check Rasi. Two breeding lines from IRRI (IR83927-B-B-278-CRA-1-1-1 and CR 2707-185-16-1-1-1) recorded a mean yield of 6,401 and 6,231 kg/ha, respectively, with a yield increase of 28% and 24%, respectively, over the check (Table 7).

In the medium-early trial, 18 hybrids and 14 inbreds were tested at five locations. The data from Pantnagar were not included in the analysis because of the low location mean yield. The mean yield of the promising entries ranged from 7,261 to 5,937 kg/ha compared with that of the check, MTU1010 (5,183 kg/ha). The top four promising entries were hybrid PAC 837, followed by RH 1531, NK6303, and DRH 834 and these hybrids recorded a yield advantage of 40%, 34%, 27%, and 27%, respectively, over the check. A breeding line from IRRI (IR65482-7-216-1-2-B) recorded a 15% yield advantage over the check (Table 8).

The medium-duration trial containing 17 hybrids and 19 inbreds was conducted at five locations. The data from Pantnagar were not considered because of low yield. The mean yield of the promising entries ranged from 6,614 to 5,841 kg/ha. The top four entries were the hybrids Indam 200-028, followed by NK 9086, DRH 836, and MRP 5402, which recorded a 21%, 17%, 17%, and 15% yield increase over the check PR 120 (5,459 kg/ha). An inbred from IRRI (IR81494-10-1-3-3-1) recorded a 7% yield advantage over the check (Table 9).

The combined analysis of the yield data of 2009 and 2010 clearly indicate the superiority of hybrid PA 6129, with a yield of 6,825 kg/ha, followed by variety Pant Dhan-16 (6,282 kg/ha) and a breeding line from IRRI (IR83927-B-B-278-CRA-1-1-1, 5,908 kg/ha) with a yield advantage of 45%, 34%, and 26% over the check Govind (4,691 kg/ha) in the early group. In the medium-early group, the promising entries were the hybrids NK 6303 (7,785 kg/ha) and NK 6754 (7,565 kg/ha) with a yield increase of 39% and 35% over the check (PR 115 in 2009 and IR64 in 2010), respectively (Table 10). These entries have been recommended for large-scale testing under mechanized DSR in farmers' fields.

Table 11 presents the combined analysis of 2010 and 2011 year data. In the early-maturity group, the highest mean yield was recorded by hybrid US 323 (7,938 kg/ha), followed by RH 257 (7,441 kg/ha) and a breeding line from IRRI, IR83927-B-B-278-CRA-1-1-1 (7,097 kg/ha). The yield advantage over the check was 43%, 34%, and 28%, respectively. In the medium-early maturity group, hybrid PAC 837 (7,441 kg/ha) and RH1531 (7,386 kg/ha) were the top entries, with a yield advantage of 44% and 43%, respectively, over the check. In the medium group, the top two entries were the hybrids Indam 200-028 (6,554 kg/ha) and MRP 5402 (6,308 kg/ha), with a mean yield increase of 17% and 13%, respectively, over the check variety. All these entries have been recommended for large-scale testing in farmers' fields (Table 11).

Table 7. Promising entries identified with early duration (2011).

Entry	Yield[a] (kg/ha)			Mean yield (kg/ha)	% Yield advantage over check	Nominating agency
	HYD	LUD	KNL			
US323	7,590	7,840	5,184	6,872	37	US Agri Seeds Ltd.
RH257	7,467	7,711	5,119	6,765	35	Dev. Gen. Ltd.
MRP5901	6,886	7,685	5,447	6,673	33	MAHYCO Ltd.
IR83927-B-B-278-CRA-1-1-1	5,474	7,299	6,431	6,401	28	IRRI
CR2707-185-16-1-1-1	5,802	8,101	4,791	6,231	24	IRRI
Rasi	4,731	4,597	5,709	5,012	–	Check

[a]HYD = Hyderabad, LUD = Ludhiana, KNL = Karnal, PTN = Pantnagar.

Table 8. Promising entries identified with medium-early duration (2011).

Entry	Yield[a] (kg/ha)				Mean yield (kg/ha)	% Yield advantage over check	Nominating agency
	HYD	LUD	KNL	PTN			
PAC 837	6,635	7,561	7,736	7,109	7,261	40	Advanta India Ltd.
RH 1531	7,017	6,133	7,766	6,825	6,935	34	Dev. Gen. Ltd.
NK 6303	5,575	7,133	8,563	5,180	6,608	27	Syngenta India Ltd.
DRH 834	5,516	6,514	8,422	5,972	6,606	27	Metahelix Ltd.
IR65482-7-216-1-2-B	4,547	4,813	7,549	6,839	5,937	15	IRRI
MTU 1010	4,354	4,586	7,270	4,523	5,183	–	Check

[a]HYD = Hyderabad, LUD = Ludhiana, KNL = Karnal, PTN = Pantnagar.

Table 9. Promising entries identified with medium duration (2011).

Entry	Yield[a] (kg/ha)				Mean yield (kg/ha)	% Yield advantage over check	Nominating agency
	HYD	LUD	KNL	PTN			
Indam 200-028	4,180	6,178	9,370	6,730	6,614	21	Indo American Hybrid Seeds Ltd.
NK 9086	6,583	–	5,610	7,050	6,414	17	Syngenta India Ltd.
DRH 836	4,522	6,166	7,678	7,076	6,360	17	Metahelix Ltd.
MRP 5402	6,868	5,343	6,608	6,303	6,280	15	MAHYCO Ltd.
IR81494-10-1-3-3-1	4,509	4,517	8,009	6,328	5,841	7	IRRI
PR 120	4,798	5,646	6,359	5,031	5,459	–	Check

[a]HYD = Hyderabad, LUD = Ludhiana, KNL = Karnal, PTN = Pantnagar.

Table 10. Promising entries identified based on 2009 and 2010 data.

Entry	Mean yield (kg/ha)	% Yield advantage over check	Nominating agency
Early-maturity group			
PA 6129	6,825	45	Bayer CropScience Ltd.
Pant Dhan-16	6,282	34	GBPUAT, Pantnagar
IR83927-B-B-278-CRA-1-1-1	5,908	26	IRRI, Philippines
Medium-early duration			
NK 6303	7,785	39	Syngenta India Ltd.
NK 6754	7,565	35	Syngenta India Ltd.

Table 11. Promising entries identified based on 2010 and 2011 data.

Entry	Mean yield (kg/ha)	% Yield advantage over check	Nominating agency
Early-maturity group			
US 323	7,938	43	US Agri Seeds Ltd.
RH 257	7,441	34	Dev. Gen. Seeds Ltd.
IR83927-B-B-278-CRA-1-1-1	7,097	28	IRRI, Philippines
Medium-early duration			
PAC 837	7,441	44	Advanta India Ltd.
RH 1531	7,386	43	Dev. Gen. Ltd.
Medium duration			
Indam 200-028	6,554	17	Indo American Hybrid Seeds Ltd.
MRP 5402	6,308	13	MAHYCO Ltd.

Performance of hybrids under zero-tillage conditions

In the wet season of 2009, 60 early-duration and 35 medium-early duration entries consisting of public- and private-bred hybrids, varieties, and breeding lines were tested in a replicated yield trial. This trial was conducted under zero-till machine-sown conditions at a Barwale Foundation farm in Hyderabad. A seed rate of 20 kg/ha was used and the standard fertilizer recommendation of 150:60:60 NPK kg/ha was used. In order to control weeds, presowing Roundup (10 days before seeding) followed by one preemergent application of pendimethalin (1 kg a.i./ha) 2 days after seeding and one postemergent application of bispyribac sodium (25 g a.i./ha) at 28 days after sowing were used. Irrigation frequency was monitored through tensiometer readings at 15-cm depth. From sowing to panicle initiation, a tensiometer reading of 20 kPa was used as the minimum threshold for re-irrigating the field. From PI to 20 days after flowering, near-saturation conditions were maintained. Need-based plant protection measures were used to control insect pests and diseases.

In the early-maturity group, promising entries identified were PA 6129 from Bayer CropScience, with a 36% yield advantage over the check Rasi, followed by

P09-023 from Pioneer (36%) and US 310 from US Agri Seeds Pvt. Ltd. (35%). In the medium-early maturity group, the top two entries were hybrids NK 6303 and NK 6320 from Syngenta India Ltd., with a 54% and 52% yield advantage over the check Krishna Hamsa, respectively (Table 12).

In the wet season of 2011, 24 entries, including hybrids and breeding lines, were evaluated at a Barwale Foundation farm. Similar crop establishment methods and a package of agronomic practices as described above were followed to raise a healthy crop. The performance of the promising hybrids is given in Table 13. US 312 hybrid from US Agri Seeds Pvt. Ltd. was the top-yielding entry with a 34% yield advantage over the best check, MTU 1010, followed by PAC 837 and PAC 801 from Advanta India Ltd. (25% and 21% yield advantage) and RH 664 from Dev. Gen. Seeds Pvt. Ltd. (21% yield advantage). Results from 2009 and 2011 clearly indicate that hybrids perform better under zero-till machine-sown DSR conditions than the respective best check varieties.

Root and shoot growth studies in hybrids

To study the root and shoot growth parameters of hybrids and check varieties grown under direct-seeded conditions, experiments were conducted in soil-filled PVC pipes.

Table 12. Promising hybrids under zero-till conditions, Hyderabad (2009).

Entry	Mean yield (t/ha)	% Yield advantage over check
Early maturity		
PA 6129	5.3	36
PO 9-023	5.3	36
US 310	5.2	35
Rasi (check)	3.9	–
Medium-early		
NK 6303	6.2	54
NK 6320	6.1	52
Arize Tej	5.9	46
Krishna Hamsa (check)	4.1	–

Table 13. Promising hybrids under zero-till conditions, Hyderabad (2011).

Entry	Mean yield (t/ha)	% Yield advantage over check
US 312	5.9	34
PAC 837	5.5	25
PAC 801	5.3	21
RH 664	5.3	21
MTU 1010 (check)	4.4	–

In the early trial, 15 entries along with the check Govind and in the medium-early trial 20 entries along with the checks MTU 1010 and IR64 were evaluated in a replicated trial. Ninety-cm PVC pipes were filled with soil mixed with vermi-compost. In each pipe, 10 seeds were sown. After germination, only five seedlings were left in each tube. At 15 days after sowing, plant height was measured in two plants from each tube and shoots of two plants were cut from the base and dry weight was recorded. At 30 days after sowing, again the height of two plants per tube was measured and those two plants were cut at the bottom to record shoot dry weight. Only one plant per tube was left till 90 days after sowing. At 90 days after sowing, plant height was recorded and the entire shoot was cut at the base and shoot dry weight recorded. The PVC pipes along with the root and soil were washed in a root washing tank till all the soil was removed and only intact and clean root mass was obtained. At this stage, root length was measured and whole root mass was oven-dried and biomass was recorded. Shoot biomass was recorded at 15, 30, and 90 days after sowing. Root and shoot growth parameters of early hybrids and the check are given in Table 14. The hybrids MRP 5631, RH 257, and US 323 recorded a significant increase in plant height at 15 DAS over the check. Highly significant shoot biomass accumulation at 30 DAS was noted in the hybrids JKRH 2007, MRP 5631, and US 323. The hybrids PA 97158 and JKRH 2007 exhibited increased root length at 90 DAS. All five hybrids recorded a highly significant increase in root biomass at 90 DAS, indicating hybrid vigor for root growth. The hybrids MRP 5631 and RH 257 recorded a significant increase in shoot biomass at 90 DAS. In the medium-early group, three hybrids (PAC 837, RH 664, and US 319) recorded increased shoot biomass at 15 DAS and two hybrids (PAC 801 and RH 664) recorded higher shoot biomass at 30 DAS. Five hybrids (PAC 801, PAC 837, RH 1531, RH 664, and US 319) recorded a significant increase in root length and root biomass at 90 days after sowing compared with the checks MTU 1010 and IR64. Four hybrids (NK 6303, PAC 837, RH 1531, and US 319) also recorded a significant increase in shoot biomass at 90 days after sowing (Table 15). All these results clearly indicate that

Table 14. Root and shoot growth traits of early-duration hybrids.[a]

Entry	PH15	BM15	PH30	BM30	PH90	TN90	RL90	RW90	BM90
PA 97158	10.3	0.110	25.3	1.51	60.5	**51.0**	**89.5**	**72.5**	50.5
JKRH 2007	14.0	**0.220**	26.0	**3.51**	71.5	35.5	**79.5**	**62.0**	38.0
MRP 5631	**16.1**	0.187	23.8	**3.26**	71.5	48.0	70.5	**61.0**	**59.5**
RH 257	**16.0**	0.163	24.0	3.15	80.5	**53.0**	77.0	**91.0**	**67.0**
US 323	**15.5**	0.186	24.8	**3.39**	76.5	41.0	72.5	**65.5**	48.0
Govind (check)	13.0	0.15	26.0	2.26	70.5	38.0	63.5	38.5	40.0
LSD (5%)	1.73	0.045	2.33	0.96	12.0	13.0	16.1	14.5	16.0
CV (%)	6	13	5	15	8	15	11	11	14

[a]Bold font indicates significance at 5%; PH15, PH30, and PH90 = plant height at 15, 30, and 90 days after sowing, respectively; BM15, BM30, and BM90 = shoot biomass at 15, 30, and 90 DAS; TN 90, RW90, and RL90 = tiller number, root biomass, and root length at 90 DAS.

Table 15. Root and shoot growth traits of medium-early hybrids.[a]

Entry	PH15	BM15	PH30	BM30	PH90	TN90	RL90	RW90	BM90
IR64	14.6	0.117	23.0	2.84	71.5	43.0	61.0	50.0	45.0
MTU 1010	14.1	0.192	23.3	3.32	67.5	38.5	64.3	54.5	38.5
NK 6303	11.4	0.116	23.6	2.79	83.0	48.5	70.0	**85.0**	**79.0**
NK 6320	13.9	0.151	27.3	3.28	83.5	39.0	67.0	**89.5**	56.0
PAC 801	15.8	0.149	24.6	**3.94**	67.0	53.5	**80.0**	**69.5**	53.5
PAC 837	14.2	**0.168**	26.0	3.46	77.5	52.5	**82.0**	**77.5**	**63.5**
RH 1531	15.9	0.148	30.5	3.78	77.5	44.0	**80.0**	**80.0**	**72.5**
RH 664	15.7	**0.230**	26.7	**4.06**	69.0	58.0	**87.5**	**66.5**	46.5
US 319	15.5	**0.176**	25.0	3.70	67.0	50.5	**90.5**	**104.5**	**61.0**
LSD (5%)	1.73	0.045	2.33	0.96	12.0	13.0	16.1	14.5	16.0
CV (%)	6	13	5	15	8	15	11	11	14
CV (%)	6	13	5	15	8	15	11	11	14

[a]Bold font indicates significance at 5%; PH15, PH30, and PH90 = plant height at 15, 30, and 90 days after sowing, respectively; BM15, BM30, and BM90 = shoot biomass at 15, 30, and 90 DAS; TN 90, RW90, and RL90 = tiller number, root biomass, and root length at 90 DAS.

hybrids have better root and shoot growth during the early stages of the crop, which is highly beneficial for better crop growth and performance under DSR conditions.

About 100 entries were screened for zinc and iron deficiency in black soil conditions under high pH (8.3). In general, hybrids were more tolerant than inbreds. Promising hybrids were JKRH 3333 from JK Agri Seeds, MRP 5402 from MAHYCO Ltd., and PAC 8512 from Advanta India Ltd. An IRRI breeding line (IR06A150) was also found to be tolerant.

We can conclude that hybrids perform better under dry DSR and heterozygosity per se and genetic plasticity of hybrids make them more suitable for DSR. Faster crop establishment, early-stage seedling vigor, and better root and shoot growth of hybrids are their added advantages under DSR. Multicrop direct-seeding machines for precise seeding and fertilizer placement help to reduce the seed rate to 15 kg/ha, which is within the permissible limits of seed rate recommended for hybrid rice. Dry direct seeding is a highly profitable and sustainable CA-based technology of the future.

Notes

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The disease scenario in Jharkhand, Bihar, and Uttar Pradesh, India, with reference to hybrid rice

Atul Kumar, Ashish Kumar, Rajesh Kumar, and Hem Chandra Lal

Rice is the staple food for 65% of the population in India. Eastern India represents the largest rice-growing area of the country yet yield is low when compared with national productivity. India needs 1.5 million tons more rice each year to keep pace with the increasing demand of the burgeoning population. Hybrid rice cultivation, if popularized among farmers of this region, can help us to achieve this target easily. Therefore, the aim of our investigation was to know what the difference is in the disease scenario when farmers grow hybrid rice in place of traditional varieties. With the popularization of intensive cultivation practices, diseases that were of minor significance are now a serious threat. Keeping this in consideration, a survey of the important hybrid rice-growing areas of Jharkhand, Bihar, and Uttar Pradesh was carried out to gather information on the disease scenario and the Standard Evaluation System of IRRI was followed to record disease incidence. Four districts (Ranchi from Jharkhand, Samastipur and Muzaffarpur from Bihar, and Bijnor from Uttar Pradesh) were the places where survey work was carried out in kharif 2009 and 2010. It was observed during the surveys in hybrid rice areas that false smut is emerging as a major disease in all the places surveyed. The major reasons behind this problem were the prevalence of new virulent isolates of the pathogen, the higher doses of nitrogenous fertilizer, and the indiscriminate use of plant protection measures.

Keywords: Hybrid rice, diseases, survey, false smut, disease occurrence, disease incidence

Rice is one of the most important and widely cultivated food crops globally and most rice (90%) is produced in Asian countries, with China and India being the major producers (IRRI 2008). The biggest problem faced by humanity in the 21st century is ensuring food security for the ever-increasing population. The current global population, estimated to be 7.1 billion, is expected to reach 7.54 billion by 2020 and 8.91

billion by 2050. Ninety-five percent of this population increase will take place in developing countries, where rice is the staple food (Hari Prasad 2012).

The productivity gains of the Green Revolution remained restricted to certain areas and have now begun to plateau as a result of ecological degradation. With this backdrop, the Indian government is looking with hope toward eastern India to bring about another Green Revolution. The government's strategy is to improve agriculture in eastern India by promoting newer technologies such as hybrid rice, which has not reached the poor marginal farmers of many states (Sahai 2012).

A state-wise analysis shows that growth in total crop output and yield fell in the post-reform period of trade liberalization in all states compared with figures for the 1980s (Bhalla and Singh 2010). Demand for rice is estimated to be 130 million tons by 2025 in India to maintain current self-sufficiency. Therefore, the major concern in coming years is to increase productivity, for which losses due to biotic stresses have to be overcome. Hybrid rice will be one of the best available options for the future enhancement of overall rice output in India. No breakthrough in rice, other than hybrid rice, would sustain India's food security during the 21st century. To break the yield barrier, hybrids have tremendous potential **(**Reddy et al 1999). It is worthwhile to point out that, compared with conventional rice varieties, hybrids are more responsive to fertilizer and have more vegetative growth, which favor disease outbreaks (Reddy 1996). However, hybrids can be grown successfully under the protection of a chemical umbrella of pesticides like any other high-yielding variety of rice (Siddiq 1996).

The Directorate of Rice Development (DRD), government of India, states that hybrid rice has increased yield by 15–20% compared with high-yielding varieties. Yet, the DRD lists many constraints to hybrid rice cultivation, including poor grain quality, the high cost of seed, susceptibility to major pests and diseases, and a lack of extension activities to guide farmers on hybrid rice cultivation (Anonymous 2002). When environmental conditions are suitable and enough water, fertilizer, and pesticide are available, hybrid rice is attractive to farmers because of its yield advantage, which is 15–20%. Our investigation was therefore undertaken to study the disease scenario in hybrid rice in Jharkhand, Bihar, and Uttar Pradesh, where the government is giving maximum emphasis to the adoption of hybrid rice cultivation.

Materials and methods

Our investigation was undertaken during kharif 2009 and kharif 2010 in selected districts of three states (Jharkhand, Bihar, and Uttar Pradesh) in India (Fig. 1). States/districts for surveys were selected on the basis of relative area and productivity of hybrid rice. Twenty-four farmers' fields from four blocks (Kanke, Ratu, Mandar, and Namkom) were selected randomly from Ranchi District in Jharkhand (Fig. 2). Likewise, 24 farmers' fields from four blocks (Pusa, Morsand, Sakra, and Musahari) were selected randomly from Samastipur and Muzaffarpur districts (Fig. 3), and 24 farmers' fields from four blocks (Kotwali, Dhampur, Afjalgarh, and Nazibabad) were selected randomly from Bijnor District in Uttar Pradesh (Fig. 4) to carry out the survey work and to observe the disease scenario in hybrid rice. Disease prevalence and disease intensity were determined as per the Standard Evaluation System of IRRI (IRRI

1996). A survey was carried out with the help of a semistructured format from various farmers' fields to record disease prevalence and disease incidence. A similar format and SES were used at all the locations to maintain homogeneity in the observations.

Results

The occurrence and relative importance of prominent hybrid rice diseases were studied and we found that false smut disease was prevalent in hybrid rice in all the districts surveyed, causing economic losses to farmers. False smut was serious and destructive in Jharkhand, causing quantitative economic loss, whereas all other diseases were present but were not economically important. Brown spot was the most serious problem in Samastipur and Muzaffarpur districts of Bihar, followed by false smut disease, whereas all other diseases were present but were not economically important. In Bijnor District of Uttar Pradesh, bacterial leaf blight was observed as the most serious and destructive disease, followed by false smut, whereas other diseases were present but were not economically important (Table 1). The results of our research can best be illustrated with the help of Tables 1 and 2 and Figures 5-7.

Fig. 1. Detailed maps of survey locations.

Fig. 2. Map of districts in Jharkhand.

Fig. 3. Map of districts in Bihar.

Disease incidence of the most popular hybrid rice variety, Pro Agro 6444, was compared with that of the most popular traditional variety, and the percent disease incidence varied from one location to another (Table 2). In Ranchi District of Jharkhand, false smut disease was the most severe and infested florets ranged from 5.2% to 26.2%, followed by blast disease, for which leaf area damage ranged from 2.2% to 6.2% (Fig. 5). In Samastipur and Muzaffarpur districts of Bihar, brown spot was the most severe disease, with percentage leaf area damage varying from 4.8% to 20.2%, followed by false smut disease, for which infested florets ranged from 2.1% to 10.5% (Fig. 6). In

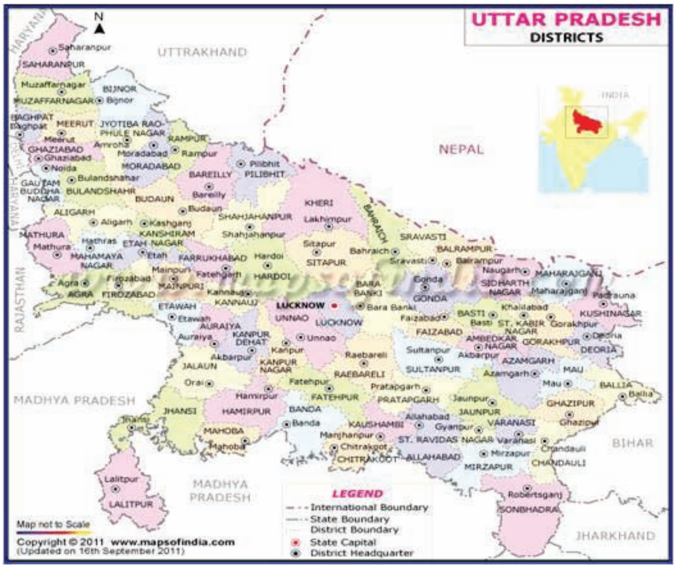

Fig. 4. Map of districts in Uttar Pradesh.

Table 1. Occurrence and relative importance of prominent hybrid rice diseases in selected states of India.

Disease (causal organism)	Disease occurrence in surveyed states/districts[a]		
	Jharkhand	Bihar	Uttar Pradesh
	Ranchi	Samastipur and Muzaffarpur	Bijnor
False smut (*Ustilaginoidea virens*)	+++	++	++
Brown spot (*Bipolaris oryzae*)	+	+++	+
Blast (*Pyricularia grisea*)	+	+	+
Bacterial leaf blight (*Xanthomonas oryzae* pv. *oryzae*)	+	+	+++
Sheath blight (*Rhizoctonia solani*)	+	+	+
Sheath rot (*Sarocladium oryzae*)	+	+	+

[a] + = Present but not economically important,
++ = serious in some places with small economic loss,
+++ = serious and destructive with quantitative economic loss.

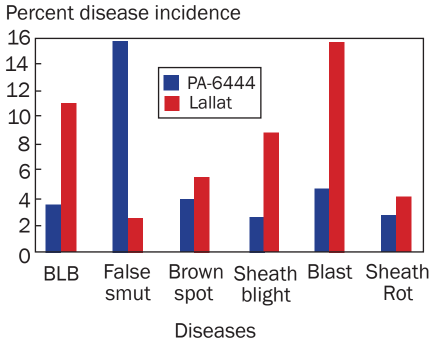

Fig. 5. Disease Scenario in Jharkand (Ranchi).

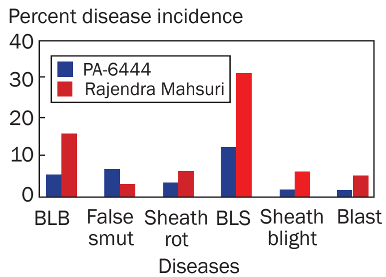

Fig. 6: Disease Scenario in Bihar (Sainastipur and Muzaffarpur).

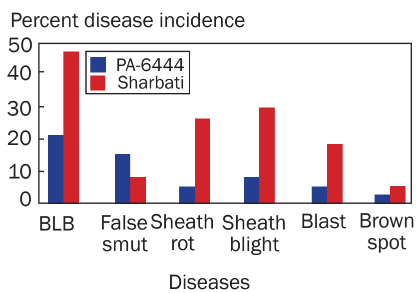

Fig. 7. Disease scenario in Uttar Pradesh (Bijnor).

Bijnor District of Uttar Pradesh, bacterial leaf blight was the most severe disease, for which percent leaf area damage ranged from 9.9% to 30.3%, followed by false smut, for which infested florets varied from 5.6% to 22.6% (Fig. 7).

Table 2. Disease incidence of the most popular hybrid rice in comparison with traditional varieties in different surveyed states of India.

States/ districts	False smut (% infested florets)				Brown spot (% leaf area damage)				Blast (% leaf area damage)			
	Hybrid rice		Traditional varieties		Hybrid rice		Traditional varieties		Hybrid rice		Traditional varieties	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Jharkhand (Ranchi)	15.7	(5.2–26.2)	2.1	(1.1–3.1)	3.6	(2.4–4.8)	5.1	(3.1–7.1)	4.2	(2.2–6.2)	15.5	(5.7–25.3)
Bihar (Samastipur and Muzaffarpur)	6.3	(2.1–10.5)	2.4	(1.2–3.6)	12.5	(4.8–20.2)	30.6	(14.9–46.3)	1.5	(0.4–2.6)	4.6	(3.1–6.1)
Uttar Pradesh (Bijnor)	14.1	(5.6–22.6)	8.4	(5.2–11.6)	1.7	(0.5–2.9)	4.6	(2.5–6.7)	3.7	(1.4–6.0)	17.2	(7.8–26.6)

States/ districts	Bacterial leaf blight (% leaf area damage)				Sheath rot (% affected tillers)				Sheath blight (% plant area damage)			
	Hybrid rice		Traditional varieties		Hybrid rice		Traditional varieties		Hybrid rice		Traditional varieties	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Jharkhand (Ranchi)	3.2	(1.2–5.2)	10.8	(8.9–12.7)	2.5	(1.1–3.9)	3.8	(1.1–6.5)	2.3	(1.0–3.6)	8.6	(3.2–14.0)
Bihar (Samastipur and Muzaffarpur)	4.6	(2.5–6.7)	15.4	(4.9–25.9)	2.7	(1.3–4.1)	5.7	(1.9–9.5)	1.8	(0.8–2.8)	5.2	(1.9–8.5)
Uttar Pradesh (Bijnor)	20.1	(9.9–30.3)	46.4	(31.9–60.9)	4.2	(2.2–6.2)	25.7	(9.9–41.5)	6.5	(2.3–10.7)	28.6	(9.7–47.5)

Discussion

The purpose of this research was to know the status of the occurrence and relative importance of various diseases in the states of Jharkhand, Bihar, and Uttar Pradesh in hybrid rice vis-à-vis traditional varieties. There is a common notion and this has been mentioned by many, including the Directorate of Rice Development, Patna (Bihar), that hybrids are susceptible to major pests and diseases (Anonymous 2002). But, in our study, this was not found to be so. If proper care is taken, hybrids have enough strength to combat common diseases such as blast, brown spot, and sheath blight, which cause substantial yield losses to farmers. Only one disease (false smut) that was observed at alarmingly higher severity at all the locations where hybrid rice was planted was found to be severe at all the places surveyed. False smut was found to be the most prominent disease in Ranchi District of Jharkhand, followed by blast and brown spot disease in hybrid rice cultivar PA 6444; but it was observed that blast, sheath blight, bacterial leaf blight, and brown spot show more severity in traditional varieties than in hybrid rice.

In Samastipur and Muzaffarpur districts of Bihar, maximum incidence of brown spot (20.2%) was seen in hybrid rice, followed by false smut; whereas, in traditional varieties, the disease incidence of brown spot was more than double (46.3%), followed by bacterial leaf blight and sheath rot, which had higher incidence than in hybrid rice cultivar PA 6444.

In Bijnor District of Uttar Pradesh, maximum disease incidence of bacterial leaf blight (30.3%) was observed in hybrid rice, followed by false smut and sheath blight; whereas, the data on disease incidence in traditional varieties indicate that bacterial leaf blight was 60.9%, which is almost double that of traditional varieties, followed by sheath blight and sheath rot diseases, which also had a higher disease severity than in hybrid rice.

This is a clear indication that hybrid rice has better resistance in fighting against major diseases except false smut, which is becoming a menace to this crop. The Green Revolution of India is one of the biggest success stories cited globally, which enabled our country to obtain self-sufficiency. In the current scenario, if this self-sufficiency is to be maintained and India need not look for surplus food grains, the only answer lies in a quicker adoption of hybrid rice production technology. More than 50 hybrids have been released in India for commercial cultivation and, out of 44 million ha under rice cultivation, only 2 million ha are occupied by hybrid rice. More than 80% of the total hybrid rice area is in four states—Uttar Pradesh, Jharkhand, Bihar, and Chhattisgarh (Viraktamath 2012). The point to ponder is why the spread is not as fast as it was in the case of the use of fertilizers or the use of high-yielding varieties in India. Our research clearly indicates that false smut disease can be a nuisance for hybrid rice cultivation if proper care is not taken soon in India. Our research is just a small effort to learn the disease scenario in these states and this needs to be thoroughly investigated in larger areas and with a larger number of samples.

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Disease resistance in hybrid rice: experience from the All India Coordinated Rice Pathology Program

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Rice productivity in India fluctuates significantly because of various biotic factors such as pests and diseases. The average yield loss from diseases and insect pests varies between 10% and 30% depending on severity. Pest and disease dynamics in hybrid rice could be slightly different as the intensity of some of diseases such as false smut has been reported to be more in hybrid rice. Host-plant resistance is the most important tool for rice disease management and has played a key role in sustaining rice productivity. Therefore, a systematic hybrid rice resistance evaluation program (National Hybrid Screening Nursery) was started at the Directorate of Rice Research to evaluate the hybrids nominated under AICRIP against major rice diseases. Since 2000, a total of 729 hybrid rice cultures were evaluated at different hot-spot locations against blast, sheath blight, brown spot, sheath rot, bacterial leaf blight, and rice tungro virus. As there was no systematic breeding program to incorporate disease resistance in parental lines, most of the hybrids evaluated did not have high resistance to rice diseases. The hybrids that exhibited good resistance to different rice diseases are discussed in this chapter. Some of the hybrids showing multiple disease resistance across India were IET # 18852, 21415, 18178, 19752, and 16841.

Rice is the staple food for more than 70% of the Indian population and it provides 43% of the calorie requirement. In India, rice is grown on an area of 44 million hectares, with annual production of 99 million tons. To meet the demand of the increasing population and to maintain self-sufficiency, current production of 99 million tons needs to be increased to 120 million tons by 2020. Though India is in a comfortable position with respect to food production, continuous efforts are required to increase food production to meet the ever-increasing population while keeping the environment clean and healthy. Because of these changed cultivation practices and apparent changes in the climate, the incidence of many pests and diseases has increased. Many diseases hitherto considered as minor have become serious in many rice-growing areas. For example, false smut of rice, which was once considered as the sign of a bumper harvest, has now become a serious problem in many rice ecosystems (Ladhalakshmi

2007, Muthuraman et al 2007. Many diseases that were earlier restricted to certain parts of the country have now spread to newer areas, for example, stem rot of rice has become a problem in parts of coastal Andhra Pradesh. Among the various strategies available for managing biotic stresses afflicting rice, the deployment of host-plant resistance is considered the most appropriate strategy since it is both economical and at the same time eco-friendly.

Hybrid rice is one of the practical, feasible, and readily adoptable technologies to increase production and productivity of rice in India. For a stable performance of hybrids across locations/seasons, the hybrids need to possess resistance to tolerance of major insect pests and diseases. Hence, the incorporation of resistance to major insect pests and diseases is one of the major objectives of the hybrid rice project. A systematic multidisciplinary and mission-mode research project on hybrid rice began in India in 1989. The entire network was coordinated by the Directorate of Rice Research in Rajendranagar, Hyderabad.

The All India Coordinated Rice Pathology Program

The All India Coordinated Rice Pathology Program of the Directorate of Rice Research is using an effective linkage and testing mechanism to assess advanced breeding lines/hybrids over a wide range of climatic and disease epidemic conditions, including state agricultural universities, national institutes, and departments of agriculture; agrochemical industry; and others to identify a broad spectrum of resistance to major rice diseases. This helps in developing need-based management methods to control the major diseases of rice. One of the major objectives of the program is to accelerate the genetic improvement of rice for resistance against the major diseases occurring in different ecosystems in the country. The rice pathology program of AICRIP involves, every year during the kharif season, an evaluation of more than 1,000 germplasm accessions and breeding lines against major rice diseases across 52 locations throughout India. Initially, different national screening nurseries (NSN1, NSN2, NSNH, and NHSN and DSN are constituted by the Plant Breeding Department. The entries include advanced breeding material in NSN1, prebreeding material in NSN2, entries bred for hill regions in NSNH and experimental hybrids in NHSN. All these sets are screened for various rice diseases at multiple locations.

All the breeding lines are also simultaneously put into screening nursery tests to identify their reaction to key pests and diseases including blast, bacterial leaf blight, sheath blight, rice tungro virus, sheath rot, and false smut. Pathologists began to evaluate and identify the promising hybrids in an Initial Hybrid Rice Trial (IHRT) along with inbred varieties in advanced variety trials in kharif 1999. Later, pathologists constituted a separate trial, the NHSN (National Hybrid Screening Nursery), to screen only hybrids. Under this screening nursery, a uniform screening method is followed for all the diseases at all hot-spot locations. Since 2000, a total of 729 hybrid rice cultures have been evaluated under the AICRIP program and some promising hybrids that possess resistance against the major diseases of rice were found.

In general, the rice crop suffers from three major groups of diseases—fungal, bacterial, and viral diseases. The important fungal diseases are blast, sheath blight, sheath rot, false smut, and brown spot and stem rot. Among the bacterial diseases prevalent in rice, bacterial leaf blight and bacterial leaf streak are considered economically important in the country. Among viral diseases, rice tungro virus is the most important. This chapter aims to present the compiled results of the national screening nursery trials conducted from 2001 to 2010. The sources of resistance identified against different diseases of rice have been tabulated. The disease scores of the test entries for each disease at different locations with a valid data set are provided as additional data tables in the accompanying DVD. To help users check the reaction of any desired entry in National Screening Nurseries, a separate list of all the nominated breeding lines with their Initial Evaluation Trial (IET) number is provided as an IET register, starting with IET No. 10,000 and above, which were evaluated during this period. Plant pathology cooperators involved in the screening trials at different AICRIP centers are detailed in Table 1. The list of abbreviations used in the publication is given in Appendices I and II.

Table 1. Screening methods followed and hot-spot locations of various rice diseases.

Disease	Screening method	Hot-spot locations
Blast	Uniform-Blast Nursery (UBN) method, tray method	Chiplima, Coimbatore, CRRI, DRR, Gangavathi, Gerua, Ghaghraghat, Gudalur, Hazaribagh, Jagadalpur, Karjat, Lonavala, Malan, Mandya, Maruteru, Mugad, Nawagam, Nellore, Pattambi, Ponnampet, Ranchi, Rewa, Umium, Varanasi, and Wangbal
Neck blast	UBN method	Chiplima, CRRI, Gerua, Ghagharaghat, Gudalur, Hazaribagh, Jagadalpur, Karjat, Lonavala, Malan, Mugad, Nawagam, Nellore, Pattambi, Ponnampet, Ranchi, Rewa, Umium, Wangbal
Brown spot	UBN or under natural field conditions	Arundhutinagar, Chatha, Ghagharaghat, Gudalur, Hazaribag, Jagadalpur, Lonavala, Ludhiana, Mandya, Moncompu, Nellore, Ponnampet, Pusa, Upper Shillong, Rewa, Umium, Varanasi
Sheath blight	Inoculation at late tillering stage (typha bit method), tooth prick method, grain-hull inoculation under field conditions	Aduthurai, Arundhutinagar, Bankura, Chatha, Chinsurah, CRRI, DRR, Faizabad, Gangavathi, Gerua, Ludhiana, Mandya, Maruteru, Moncompu, Pantnagar, Pattambi, Port Blair, Raipur, Titabar
Sheath rot	Multiply pathogen on autoclaved rice grains. Spray spore suspension at booting stage.	Aduthurai, Bankura, Chatha, Chinsurah, Lonavala, Mandya, Maruteru, Moncompu, Nawagam, Nellore, Patna, Pantnagar, Puducherry, Pusa, Ragolu, Raipur, Rajendranagar
Bacterial blight	Leaf clipping method, root dip method, pin prick method	Aduthurai, Arundhutinagar, Chinsurah, Chiplima, CRRI, DRR, Faizabad,Gangavathi, Karaikal, Karjat, Kaul, Ludhiana, Maruteru, Navasari, Nawagam, Nellore, Patna, Pantnagar, Pattambi, Raipur, Titabar
Rice tungro virus	Leafhopper transmission	Chinsurah, Coimbatore, CRRI, DRR, Pondicherry, Tirur

Many of the lines mentioned in this chapter are not suited for adoption as varieties for commercial cultivation; the most promising lines are being registered with NBPGR as improved germplasm and are available for use by any interested rice breeder. Thus, this chapter is unique and has multiple uses. First, any rice pathologists or rice breeders who nominated entries for evaluation can readily check the performance of their cultures across years against all the diseases tested. Second, three years of data for disease-resistance traits from NSN, along with their varietal information, can be obtained and submitted for consideration of the Varietal Identification Committee (VIC). Finally, the most promising new lines can be further studied for possible discovery of new genes/QTLs and their use. We also hope that the additional information on the cultural characteristics of the pathogen, isolation and inoculation techniques, and screening methods provided in this chapter will be useful to plant pathologists and plant breeders to initiate further studies on host-plant resistance in rice against diseases.

Multilocation evaluation of the hybrids

The multilocation evaluation trials are routinely conducted by every state in most crops in various well-identified agro-climatic zones to identify a variety/hybrid suitable for these zones. In rice also, multilocation evaluation of promising experimental hybrids at 25–30 locations representing different agro-climatic zones of the country is the major activity in the hybrid rice network, coordinated by the Directorate of Rice Research, Hyderabad, through which hybrids are tested in replicated trials. Breeders across the country nominate their best hybrids based on their performance in preliminary replicated yield trials for evaluation in nationwide multilocation trials.

In the hybrid rice network system, the experimental hybrids developed by the network centers and private seed companies are pooled together based on duration and are evaluated in Initial Hybrid Rice Trials (IHRT) at 25 to 30 locations. Each nominated hybrid entry is assigned an IET (Initial Evaluation Testing) number, which indicates its identity. An entry possessing an IET number suggests that it has undergone multilocation testing in the AICRIP trials. The Initial Hybrid Rice Trial comprises only experimental hybrids and the corresponding checks, whereas in AVT-1 and AVT-2 trials, promising hybrids are compared with promising elite inbred lines. Test hybrids that record more than a 5% yield advantage over the best hybrid check and a 10% yield advantage over the best varietal check and that confirm to quality (HRT-MS trial) are promoted to the next stage of testing.

The rice disease scenario in India

Blast

Rice blast is the most severe disease of rice (DRR 1975-2010). The disease is caused by the fungus *Magnaporthe grisea* (anamorph: *Pyricularia grisea*). The disease is especially more serious in humid temperate areas, uplands, and hilly areas. Rice blast disease is endemic in upland areas of Jharkhand, Madhya Pradesh, Chhattisgarh, Maharashtra, Gujarat, and Odisha; hilly regions of northwestern and northeastern states such as Himachal Pradesh, Jammu and Kashmir, Uttarakhand, Meghalaya, Manipur, Tripura, Arunachal Pradesh, and northern districts of West Bengal; and hilly and cooler regions of southern states such as Karnataka, Tamil Nadu, Andhra Pradesh, and Kerala (Muthuraman et al 2008). The disease is also a major problem in Penna River belts and the Godavari and Thanjavur delta regions of southern India. Outbreaks of this disease in epidemic forms have been reported from many rice-growing areas. The yield losses from this disease may reach 75% or more (Ou 1985). Temperature and relative humidity play an important role in epidemics of the disease. Low night temperature (below 24 °C) alternating with a day temperature of around 28-30 °C coupled with high relative humidity (more than 90%) favor disease development. Frequent rains, continuous spells of cloudy weather, dew, fog, and high relative humidity favor the rapid build up of the disease. High nitrogen application markedly increases the intensity of the disease.

Sheath blight

Sheath blight of rice caused by the fungus *Rhizoctonia solani* Kuhn [teleomorph: *Thanatephorus cucumeris* (Frank) Donk] is the second most important disease after blast. The yield losses from this disease can vary from 20% to 50% depending on environmental conditions, the crop stage at which the disease appears, cultivation practices and cultivars (Ou 1985, Nagaraj Kumar et al 2005). It is a serious problem in the irrigated rice ecosystem, especially in coastal areas and areas with frequent rainfall and high humidity. In the boro season, the disease has been observed regularly in moderate form in Assam, Bihar, and eastern Uttar Pradesh. The disease is aggravated with the heavy application of nitrogenous fertilizers. In addition to *R. solani*, which causes sheath blight, two other species of *Rhizoctonia* have been found to be associated with this disease. These two pathogens are *R. oryzae* and *R. oryzae-sativae* which cause sheath spot and aggregated sheath spot of rice, respectively, and they can occur concurrently. Thus, this is sometimes referred to as rice sheath blight disease complex.

Sheath rot

This disease is caused by the fungus *Sarocladium oryzae*. Once considered a minor disease, it has assumed serious proportions and has become a significant production constraint. The intensity of the disease is higher in crops affected by stem borer, rice tungro disease, and various other biotic and abiotic stresses (Ou 1985). The disease is of common occurrence on cytoplasmic male sterile lines (A lines) in hybrid rice seed production plots (Laha and Muthuraman 2009). The extent of yield loss from this disease is dependent on several biotic and abiotic factors. Sheath rot infection greatly influences different yield components such as panicle weight and total number of filled grains. Moreover, the grains in sheath rot-infected plants are discolored and grains break during milling. Yield loss from this disease may reach 50% or more. A severe outbreak of sheath rot occurred in Punjab during the 1978-79 wet season, when there were reports of heavy yield loss (Raina and Singh 1980).

Brown spot

This disease is caused by the fungus *Helminthosporium oryzae* (synonym: *Drechslera oryzae*; teleomorph: *Cochliobolus miyabeanus*). The disease is a problem mainly during the kharif season, especially in uplands and the hill ecosystem. The disease also assumes a serious proportion in the irrigated ecosystem, especially in ill-managed plots. The disease can be a serious problem in aerobic rice.

False smut

False smut, once considered as a minor and sporadic disease of rice, has emerged as a serious problem, especially in high-yielding and hybrid rice varieties in many rice-growing areas. Most of the released hybrids were found susceptible under field conditions. False smut is caused by the fungus *Ustilaginoidea virens* (teleomorph: *Claviceps oryzae-sativae*). Late-maturing varieties show a greater incidence of the disease than varieties that flower and set grains early. Yield loss is not only due to the occurrence of smut balls but also due to the increased sterility of kernels neighboring the smut balls. Yield losses ranging from 0.2% to 75% have been reported in different rice varieties by different workers (Dodan and Singh 1996). Environmental factors and host nutrition, especially at the time of flowering have a definite influence on the occurrence of false smut disease. A high dose of nitrogen fertilizer at the time of flowering aggravates the disease. A lower maximum and minimum temperature coupled with less sunshine or cloudy days during the flowering period favor disease development (Muthuraman et al 2008).

Grain discoloration

Grain discoloration of rice has become a serious problem in recent years, especially when postflowering rain occurs. A variety of organisms have been found to be associated with grain discoloration of rice: *Drechslera oryzae, Sarocladium oryzae, Alternaria padwickii, Curvularia* spp., *Epicoccum* sp., *Fusarium moniliforme*, etc. In addition to yield loss, a high amount of breakage occurs in infected grains.

Stem rot

Stem rot of rice has become an important disease, causing substantial losses due to increased lodging. This disease is caused by the fungus *Sclerotium oryzae*. Stem rot is favored by high N fertilizer use, high relative humidity, high temperature, and waterlogging. The disease occurs more in early planted crops because of the high temperature and relative humidity that prevail during the susceptible stage of the crop. Stem root is prevalent in Haryana, Bihar, Uttaranchal, and Andhra Pradesh.

Foot rot or bakanae

This disease is caused by the fungus *Fusarium moniliforme* (teleomorph: *Gibberella fujikuroi*). The most conspicuous and common symptom of the disease is bakanae (i.e., abnormal elongation of the plants). Infected plants have tall lanky tillers bearing pale green leaves, which are conspicuous above the general level of the crop. Infected plants have fewer tillers and the leaves dry up one after another. White powdery growth of the conidiophores can be seen over the lower regions of diseased plants. Though the disease is of limited occurrence, it has potential to be severe. It is prevalent in Haryana, Punjab, Tamil Nadu, and Andhra Pradesh.

Bacterial blight of rice

In India, bacterial blight (BB) of rice caused by *Xanthomonas oryzae* pv. *oryzae* (*Xoo*) is considered as one of the most destructive diseases, especially in irrigated and rainfed lowland ecosystems. BB epidemics in northwestern India during 1979 and 1980 (DRR 1979, 1980) and in parts of Kerala during 1998 (Priyadarishini and Gnanamanickam 1999) are some examples of its destructive nature. Yield losses of 20–30% in moderate intensity and up to 50% in severe intensity have been reported in several parts of Asian countries (Rao and Kauffman 1971, Singh et al 1977, Mew 1987). This is essentially a monsoon season disease. The disease is prevalent in moderate to severe form in almost all rice-growing areas during the monsoon season. The intensity of the disease is strongly influenced by rainfall and cloudy, drizzling, and stormy weather and high nitrogen fertilizer use.

Rice tungro disease

This is the most important virus disease of rice. Rice tungro disease is a composite disease caused by two unrelated viruses, rice tungro bacilliform virus (RTBV) and rice tungro spherical virus (RTSV). RTSV is a plant picornavirus with a single-stranded positive-sense RNA genome while RTBV is a pararetrovirus, with a double-stranded and circular DNA genome. RTBV resembles the members of the Badnavirus (bacilliform DNA virus) group. The disease has been reported in many rice-growing areas of India. It is prevalent in Tamil Nadu, West Bengal, parts of Andhra Pradesh, and Odisha. If the disease appears during the early stages of growth, yield losses may reach 70-80% or more depending on the varieties (Krishnaveni et al 2007).

In addition to these diseases, several minor rice diseases may under favorable conditions assume serious proportions. Some rice diseases of minor importance are leaf scald, narrow brown leaf spot, udbatta, kernel smut, bacterial leaf streak, rice grassy stunt virus, and rice ragged stunt virus.

Sources of resistance

Disease resistance screening trials are conducted at AICRIP (DRR) with a specific set of entries that are evaluated by adopting a uniform screening method (Table 1). The performance of the test entry against all diseases is compared with that of the check variety across the locations. This performance is influenced by relative disease pressure or location severity index (LSI) of the test center. Thus, it is not expected that disease pressure will be uniform at different locations during the same testing season or uniform at the same location over different testing seasons. In this regard, the data from the locations that did not show the required disease pressure for a particular disease were not considered for selecting the best entry. The performance of an entry was rated across the test locations for each year of testing. The number of promising tests (NPT) was computed for each entry based on the number of locations recording a severity index less than or equal to 3 based on the SES scale (IRRI 1996) of the respective disease. Promising entries for each year of testing were picked, again subject to not more than 10% of the total entries tested. For each disease, promising entries were selected from all the relevant trials involving tests against the disease.

Since 2000, a total of 729 hybrid rice cultures have been evaluated at different hot-spot locations against blast, sheath blight, brown spot, sheath rot, bacterial leaf blight, and rice tungro virus. As there was no systematic breeding program to incorporate disease resistance in parental lines, most of the hybrids evaluated did not have high resistance to rice diseases. The hybrids that exhibited good resistance to different rice diseases are discussed in this chapter. Some of the hybrids showing multiple disease resistance across India were IET # 18852, 21415, 18178, 19752, and 16841 (Table 2).

Conclusions and future prospects

Though many options exist for the management of plant diseases such as physical, cultural, biological, and chemical methods, host-plant resistance stood out top as the most priority as it is eco-friendly and cost-effective. Using hybrids with multiple disease resistance is the major strategy to combat two or more diseases simultaneously. Under the AICRIP program, screening methods for all major rice diseases are well developed. More effort is required to develop isolation and inoculation procedures for emerging diseases such as false smut, bakanae, and leaf scald. The use of molecular markers in introgression and pyramiding resistance genes for both blast and BLB has become an advantage to enhance precision in the development of hybrids with multiple disease resistance.

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Table 2. Promising hybrid rice entries with resistance to different diseases.

Year	Total no. tested	Entries with SI ≤ 3	Promising entries (IET/designation)
Blast 2000	40	12	IHRT-E-2, IHRT-E-7, IHRT-E-8, IHRT-ME-1, IHRT-ME-2, IHRT-ME-3, IHRT-ME-4, IHRT-ME-11, IHRT-ME-12, IHRT-ME-13, IHRT-ME-17, IHRT-M-5 4
2001	42	16	IHRT-E-2, IHRT-ME-4, IHRT-ME-6, IHRT-ME-8, IHRT-ME-13, IHRT-ME-15, IHRT-M-1, IHRT-M-11
2002	55	9	IHRT-E-2, IHRT-E-3, IHRT-E-5, IHRT-E-7, IHRT-E-8, IHRT-E-9, IHRT-ME-10, IHRT-M-5, IHRT-M-6
2003	52	12	IET nos.18136, 18144, 18156, 18157, 18162, 18166, 18173, 18178, 18179, 18180, 18195
2004	72	8	IET nos. 18862, 18858, 18829, 18816, 18859, 18834, 18815, 18827
2005	60	4	IET nos. 19518, 19528, 19529, 18849
2006	17	5	IET nos. 19738, 19746, 19749, 19754, 19755
2007	66	28	IET nos. 20403, 20404, 20407, 20408, 20413, 20414, 20415, 20416, 20422, 20426, 20427, 20428, 20429, 20430, 20431, 20432, 20433, 20434, 20438, 20439, 20440, 20441, 20442, 20444, 20446, 20447, 20453, 20456
2008	15	14	IET nos. 20715, 20721, 20726, 20756, 20736, 20738, 20716, 20720, 20722, 20723, 20730, 20709, 20710, 20459
2009	20	13	IET nos. 21431, 21415, 21405, 21408, 21427, 21401, 21404, 21429, 21407, 21422, 21403, 21444, 21432
2010	22	13	IET nos. 21807, 21806, 21787, 21801, 21810, 21770, 21774, 21800, 20755, 21829, 21812, 21771, 21783
2011	18	18	IET nos. 22345, 22346, 22370, 22371, 22376, 22394, 22399, 22384, 21826, 22352, 22362, 22363, 22364, 22369, 22374, 22326, 22383, 22400
Neck blast 2006	48	11	IET nos.19754, 19530, 19735, 19737, 19741, 19755, 19757, 19760, 19763, 19542, 19767
2007	66	13	IET nos. 20447, 20403, 20429, 20446, 20457, 20413, 20422, 20426, 20453, 20434, 20443, 20448, 20455
2008	57	15	IET nos. 20749, 20715, 20716, 20741, 20460, 20750, 20751, 20711, 20752, 19766, 20756, 20744, 20717, 20720, 20724
2009	63	5	IET nos. 21415, 21434, 20752, 20758, 20460
2010	82	6	IET nos. 20755, 21771, 21777, 21784, 21817, 21819
2011	107	1	IET no. 22353
Sheath blight 2000	40	5	IHRT-E-1, IHRT-ME-11, IHRT-M-10, IHRT-M-11, IHRT-M-12

continued

Table 2. Continued.

Year	Total no. tested	Entries with SI ≤ 3	Promising entries (IET/designation)
2001	42	1	IHRT-ME-12, IHRT-M-1, IHRT-M-9, IHRT-M-2, IHRT-M-5
2002	55	22	IHRT-E-5 to IHRT-E-7, IHRT-E-9 to IHRT-E-11, IHRT-ME-2 to IHRT-ME-4, IHRT-ME-6, IHRT-ME-9 to IIHRT-ME-11, IHRT-ME-15, IHRT-ME-16, IHRT-ME-20, IHRT-ME-21, IHRT-M-1, IHRT-M-5, IHRT-M-7, IHRT-M-9, IHRT-M-16
2003	52	7	IET nos. 18149, 18160, 18281, 18169, 18173, 18178, 18283
2004	72	7	IET nos. 18873, 18875, 18866, 18876, 18834, 18870, 18867
2005	60	2	IET nos. 19539, 18849
2006	48	5	IET nos. 19744, 19746, 19750, 19752, 19753
2007	66	11	IET nos. 20450, 20444, 20451, 20447, 20457, 20433, 20442, 20448, 20452, 20453, 20439
2008	57	13	IET nos. 20756, 20740, 20721, 20733, 20459, 20757, 20758, 20759, 20746, 20722, 20729, 20749, 20750
2009	63	7	IET nos. 21441, 21449, 21442, 21434, 21402, 21432, 21433
2010	82	8	IET nos. 21782, 21808, 21811, 21807, 21820, 20759, 21804, 21832
2011	107	1	IET no. 22400
Sheath rot 2000	40	10	IHRT-E-6, IHRT-E-7, IHRT-ME-3, IHRT-ME-9, IHRT-M-7, IHRT-M-8, IHRT-M-9, IHRT-M-11, IHRT-M-12, IHRT-M-13
2001	42	10	IHRT-E-1, IHRT-E-3, IHRT-ME-12, IHRT-ME-13, IHRT-M-3, IHRT-M-4, IHRT-M-6, IHRT-M-10, IHRT-M-12, IHRT-M-14
2002	55	11	IHRT-M-14, IHRT-ME-1, IHRT-ME-9, IHRT-ME-13, IHRT-M-18, IHRT-M-13, IHRT-M-12, IHRT-M-15, IHRT-E-5, IHRT-E-8, KRH-2
2003	52	8	IET nos. 18147, 18282, 18165, 18172, 18174, 18177, 18179, 18195
2004	72	10	IET nos. 18865, 18808, 18834, 18810, 18825, 18876, 18855, 18805, 18853, 18877
2005	60	2	IET nos. 19494, 19535
2006	48	Nil	–
2007	66	6	IET nos. 20417, 20421, 20457, 20460, 20453, 19766
2008	57	6	IET nos. 20723, 20722, 20721, 20733, 20728, 20745
2009	63	1	IET no. 21398
2010	82	10	IET nos. 21816, 21793, 21811, 21821, 21832, 21817, 21800, 21801, 21812, 21827
2011	107	14	IET nos. 22394, 21827, 22382, 22364, 22343, 22373, 22381, 22366, 22400, 22370, 22359, 22387, 22385, 22365

continued

Table 2. Continued.

Year	Total no. tested	Entries with SI ≤ 3	Promising entries (IET/designation)
Bacterial leaf blight 2000	40	1	IHRT-ME-15
2001	42	0	–
2002	55	0	–
2003	52	0	–
2004	72	0	–
2005	60	1	IET nos. 19504/NK 7125
2006	48	0	–
2007	66	0	–
2008	57	4	IET nos. 20713, 20754, 20722, 20723
2009	63	4	IET nos. 21423 (VNR-203), 21443 (CRHR-48), 21414 (IRH-52), 21400 (US-310)
2010	82	4	IET nos. 21447, 21780, 21829, 21826
2011	107	14	IET nos. 22362 (HRI-176), 22379 (HRI-174), 22323 (HRI-175), 22380 (HRI-177), 21826 (US-303), 22391 (MTUHR-2096), 22381 (HRI-178), 22395 (CRHR-36), 22396 (US-341), 22397 (US-344), 22394 (CRHR-33), 22401 (PAN-812), 22343 (RH-9009), 22384 (KPH-382)
Rice tungro disease 2000	40	6	IHRT-E-8, IHRT-ME-4, IHRT-ME-6, IHRT-ME-9, IHRT-ME10, IHRT-ME-13
2001	42	14	IHRT-ME-1 & 2, IHRT-ME-9, IHRT-ME-5, IHRT-ME-6, IHRT-ME-10, IHRT-M-2, IHRT-M-9, IHRT-M-11, IHRT-M-14, IHRT-M-15, IHRT-M-16, IHRT-E-2, IHRT-E-6
2002	55	27	IHRT-E-1, IHRT-E-2, IHRT-E-4, IHRT-E-10, IHRT-E-11, IHRT-ME-1, IHRT-ME-2, IHRT-ME-4, IHRT-ME-6, IHRT-ME-7, IHRT-ME-11, IHRT-ME-12, IHRT-ME-14, IHRT-ME-18, IHRT-ME-19, IHRT-ME-20, IHRT-ME-21, IHRT-M-4, IHRT-M-5, IHRT-M-9, IHRT-M-13, IHRT-M-16, IHRT-M-19, IHRT-M-20, IHRT-M-21, IHRT-M-22, IHRT-M-23
2003	52	8	IET nos. 18137, 18141, 18144, 18145, 18146, 18151, 18163
2004	72	7	IET nos. 18855, 18820, 18847, 18852, 18857, 18860, 18866
2005	60	7	IET nos. 19497, 19504, 19514, 19520, 19523, 18849, 18852
2006	48	1	IET no. 19742
2007	66	3	IET nos. 20409, 20421, 20442

continued

Table 2. Continued.

Year	Total no. tested	Entries with SI ≤ 3	Promising entries (IET/designation)
2008	57	11	IET nos. 20722, 20715, 20720, 20721, 20731, 19766, 20755, 20461, 20740, 20739, 20746
2010	82	8	IET nos. 21781, 21805, 21814, 21815, 21831, 21793, 21818, 21823
2011	107	–	Nil

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Performance of rice varieties and hybrids under intermittent irrigation

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The concept of alternate wetting and drying (AWD) is to save water resources while maintaing high productivity in irrigated rice ecosystem. Field experiments were conducted with alternate weekly wetting and drying cycles, starting from 15 days after planting through maturity, whereas normal irrigation served as the control during the rabi season of 2007-08 and 2008-09. Our study revealed that plants under intermittent irrigation flowered 3 days earlier than the check plants. The TDM for all varieties and hybrids recorded a significant (11.5%) reduction under intermittent irrigation. The reduction in TDM ranged from –5.8% (Triguna) to (–12.8% (PHB-71). The mean 1,000-grain weight for all varieties decreased by 6.7% under intermittent irrigation. Triguna recorded the maximum reduction (10.2%) and the reduction was lowest (4.2%) in PA-6201. Mean grain yield was significantly lower (–15.2%) for all the entries under intermittent irrigation. The reduction was higher (–15.2%) in PA-6201 whereas in CORH3 it was lower (–4.5%) under intermittent irrigation. Based on this 2-year study the genotypes CORH 3, PA-6444, PHB-71, CO 49, Naveen, CB 01 001, and CB 05 501 recorded early flowering, higher flag leaf area, lower canopy temperature, increased relative water content, and a lower grain yield reduction under intermittent irrigation. In the 2-year study, hybrid CORH 3 (–4.5% to 6.2%) and Naveen (-6.2% to 9.3%) had a lower yield reduction under intermittent irrigation. Thus, these genotypes can be recommended for water-scarce areas with intermittent irrigation.

Introduction

Irrigated rice in Asia is a prolific user of water and it uses two to three times more water than other important cereals such as wheat and maize. Tuong and Bouman (2003) estimate that, by 2025, about 2 million ha of Asia's irrigated dry-season rice and 13 million ha of its irrigated wet-season rice will experience "physical water scarcity," and most of the 22 million ha of irrigated dry-season rice in South and Southeast

Asia will suffer “economic water scarcity.” To meet the major challenge—rice production needs to increase to feed a growing population under increasing scarcity of water resources—alternate wetting and drying (AWD) irrigation has been developed as a novel water-saving technique and adopted in many countries such as China, Bangladesh, India, and Vietnam (Tuong et al 2005, Bouman 2007, Yang et al 2007, Zhang et al 2008, 2009). This technique, characterized by its alternation of periods of soil submergence with periods of nonsubmergence during the growing season, could substantially reduce irrigation water and lead to an improvement in water-use efficiency (WUE) (Belder et al 2004, 2005, Zhang et al 2008). It has been reported that, when compared with continuously submerged conditions, AWD irrigation can maintain or even increase grain yield (Tuong et al 2005, Yang et al 2007, Zhang et al 2008, 2009). To overcome this problem of severe water shortage for rice production, we urgently need new methods of irrigation to save water and related crop management technologies to sustain yield (Tuong and Bouman 2003).

Materials and methods

Field experiments were conducted at a research farm of the Department of Rice, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India, during the rabi season of 2007-08 and 2008-09. The experiments were laid out in two separate independent RBD sets with three replications each. The main treatments were intermittent irrigation (7 days alternate dry and wet conditions) vs. normal irrigated conditions.

The subtreatments were

Rabi 2007-08

Four hybrids:	CORH 3, PA-6201, PA-6444, and PHB-71
Four varieties:	CO 48, Krishna Hamsa, MTU-1010, and Naveen

Rabi 2008-09

Three hybrids:	CORH 3, PA-6201, and PHB-71
Five varieties:	CO 49, Triguna, Naveen, CB 01 001, and CB 05 501

The normal irrigated (control) block was selected in an adjacent field while the aerobic plot was laid out with double channels all around the experimental plots to prevent lateral water flow. In the aerobic set, mid-season drainage (7d–7d alternate dry and wet conditions) was given from 15 days after planting (DAP) to maturity. The recommended cultural operations were followed. Five plants were collected from each set and replications to record observations on different physiological, growth, and yield characters at different crop stages. The data collected underwent statistical analysis (Gomez and Gomez 1984).

Results and discussion

Rabi 2007-08

Plant height. The impact of mid-season drainage showed that the plant height of all genotypes decreased significantly compared to normal irrigated conditions. Genotype CO 48 recorded higher plant height in irrigated conditions (124 cm) but lower in mid-season drainage (105 cm) and at maturity (Table 2).

Days to 50% flowering. Early flowering was reported in all genotypes under mid-season drainage conditions. Among the genotypes, Krishna Hamsa flowered earlier (85 days) than the other genotypes. This was followed by PHB-71 and CORH 3 (Table 2).

Flag leaf area. Hybrids PA-6444, PA-6201, and CORH 3 maintained higher flag leaf area under intermittent irrigation than the other varieties (Table 2).

SPAD value. The relative value of chlorophyll content was higher in PHB-71 (37), CORH 3 (37), and Naveen (35) under intermittent irrigation (Table 2).

Canopy temperature difference (CTD). The crop canopy temperature was influenced not only by soil water content but also by air temperature; therefore, the difference in canopy-air temperatures (Tc - Ta) could be used as an index for diagnosing crop water status. In our study, the hybrids PHB-71 and CORH 3 and variety MTU 1010 showed less canopy temperature difference (4.8, 5.0, and 5.3) under mid-season drainage than in normal conditions (Table 2).

Panicle dry weight. Significantly higher panicle dry weight accumulated in PA-6444 (3.18 g), CORH 3 (2.57 g) and Naveen (2.78 g) under alternate dry and wet conditions (Table 1).

Yield and yield components. The genotypes had considerable variation in grain yield and yield components under alternate dry and wet conditions. The number of panicles/m^2 was higher in CORH 3 (204), PA-6444 (203), and PHB-71 (202) under alternate dry and wet conditions. But, the number of grains developed per panicle was significantly higher in CORH 3 (175), CO 48 (168), and PA-6444 (164). All the genotypes produced significantly higher grain yield (g/m^2) in normal irrigated conditions than in mid-season drainage treatments. PA-6444 (596 g/m^2) showed higher yield

Table 1. Impact of mid-season drainage on plant height and yield components of rice.

Entry	Plant height at PM		Per panicle dry weight		No. panicles/m^2		Grain number per panicle	
	Normal	Intermittent	Normal	Intermittent	Normal	Intermittent	Normal	Intermittent
CO 48	110	96	2.91	2.35	219.3	185.3	184.0	166.0
Kr. Hamsa	63	60	2.34	1.73	217.4	188.0	112.7	90.3
MTU 1010	74	64	2.39	1.98	214.4	186.8	136.0	93.4
Naveen	88	72	2.82	2.78	202.1	191.3	151.2	135.3
CORH 3	69	63	2.96	2.57	239.3	204.3	201.3	174.7
PA-6201	74	69	2.54	2.17	220.0	200.1	147.3	125.2
PA-6444	84	74	3.30	3.18	226.6	203.2	187.1	163.6
PHB-71	79	72	3.20	2.49	262.3	202.0	157.1	118.1
	SED	CD at 5%	SED	CD at 5%	SED	CD at 5%	SED	CD at 5%
N	0.78	1.62	0.06	0.13	4.16	8.5	2.92	5.96
I	1.59	3.25	0.13	0.27	8.32	16.9	5.84	11.92
N x I	2.25	4.60	0.18	NS	11.8	NS	8.36	16.86

NS = nonsignificant.

under alternate dry and wet conditions as well as in normal irrigated conditions, followed by Naveen (579 g/m^2), PHB-71 (543 g/m^2), and CORH 3 (529 g/m^2) (Fig . 1).

Rabi 2008-09

Plant height. The impact of intermittent irrigation showed that the plant height of all genotypes decreased significantly compared with normal irrigated conditions. CB 01 001 recorded higher plant height in irrigated conditions (104 cm) and lower in intermittent irrigation (88 cm) at maturity. The lowest height was observed in CORH 3 (69 and 63, respectively) (Table 3).

Table 2. Impact of intermittent irrigation on phenology and physiology of rice.

Entry	50% flowering		Flag leaf area at flowering (cm^2)		SPAD reading at flowering		Canopy temp. depression CTD at flowering (C_t - C_a)	
	Normal	Intermittent	Normal	Intermittent	Normal	Intermittent	Normal	Intermittent
CO 48	109	102	32.4	26.9	38.3	33.4	9.2	6.1
Kr. Hamsa	88	85	22.5	17.5	37.2	32.1	9.5	7.2
MTU 1010	91	89	25.1	21.6	39.9	32.6	8.0	5.3
Naveen	92	89	29.5	23.9	39.3	35.2	8.2	6.6
CORH 3	90	84	30.5	28.3	40.5	36.8	7.3	5.0
PA-6201	92	89	31.9	30.4	38.5	31.4	8.1	6.2
PA-6444	99	96	33.7	31.2	38.1	32.7	9.6	7.5
PHB-71	89	86	30.6	24.9	40.8	37.0	8.4	4.8
	SED	CD at 5%	SED	CD at 5%	SED	CD at 5%	SED	CD at 5%
N	0.47	0.96	0.49	0.99	0.38	0.78	0.28	0.57
I	0.94	1.91	0.98	1.99	0.77	1.57	0.56	1.15
N x I	1.32	NS	1.38	NS	1.09	2.22	0.79	1.62

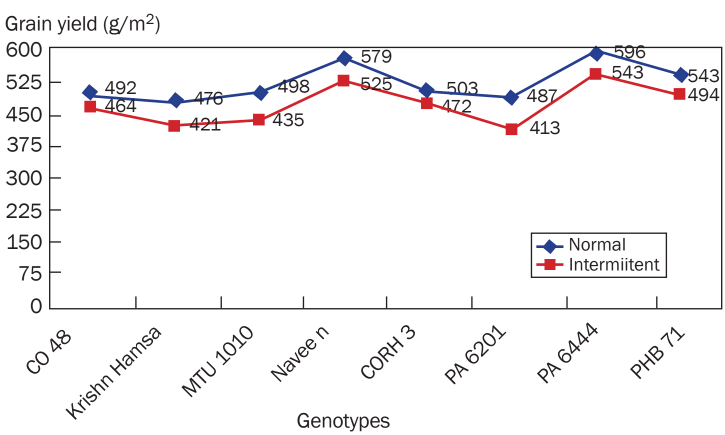

Fig. 1. Grain yield in g/m^2.

Table 3. Impact of mid-season drainage on plant height and yield components of rice.

Entry	Plant height (cm) at PM		Per panicle dry weight (g/m²)		No. panicles/m²		Grain number per panicle	
	Normal	Intermittent	Normal	Intermittent	Normal	Intermittent	Normal	Intermittent
CO 49	78	71	2.85	2.65	305	280	176	151
CB 01 001	104	88	2.96	2.83	310	275	171	146
CB 05 501	82	72	3.23	3.03	314	283	257	231
Naveen	88	72	2.82	2.66	314	258	162	144
Triguna	86	70	2.92	2.68	284	229	144	130
CORH 3	69	63	2.96	2.64	302	265	223	194
PA-6201	78	69	2.54	2.17	290	259	168	126
PHB-71	79	72	3.20	2.49	272	243	176	118
	SED	CD at 5%	SED	CD at 5%	SED	CD at 5%	SED	CD at 5%
N	0.74	1.52	0.04	0.90	3.50	7.15	2.95	6.05
I	1.49	3.05	0.09	0.19	7.01	14.32	5.91	12.00
N x I	2.11	4.30	0.13	NS	9.91	NS	8.15	17.05

NS = nonsignificant.

Days to 50% flowering. Early flowering was reported in all genotypes under intermittent irrigation. Among the genotypes, Naveen flowered earlier (80 days) than the other genotypes, followed by CORH 3 (83 days) and PHB-71 (85 days) (Table 4).

Canopy temperature difference (CTD). The hybrids Naveen, CORH 3, and variety CO 49 showed less canopy temperature difference (4.8, 5.3, and 6.1) under intermittent irrigation than in normal conditions (Table 4).

Relative water content. Almost all the genotypes showed a considerably reduction in RWC under intermittent irrigation. The maximum RWC was observed in CORH 3 (87.4%) under intermittent irrigation (Table 4).

Grain yield and yield components. The rice genotypes had considerable variation in grain yield and yield components under intermittent irrigation. Per panicle dry weight and number of panicles/m^2 were higher in CB 05 501 (3 g and 283) but the lowest per panicle dry weight was recorded in PA-6201 (2.2 g) under intermittent irrigation (Table 3). However, grain number per panicle was higher in CB 05 501 and CORH 3 in both irrigation treatments. All the genotypes produced significantly higher grain yield (g/m^2) in normal irrigated treatments than in mid-season drainage treatments. Naveen (573 g/m^2) showed higher yield under both intermittent irrigation and normal irrigated conditions, followed by CB 01 001 (524 g/m^2),CB 501 (513 g/m^2), and CORH 3 (500 g/m^2) (Fig. 2).

Pooled two year data observations. Based on the 2-year study, genotypes CORH 3, PA-6444, PHB-71, CO 49, Naveen, CB 01 001, and CB 05 501 recorded early flowering, higher flag leaf area, lower canopy temperature, increased relative water content, and a lower grain yield reduction under intermittent irrigation.

In the 2-year study, hybrids CORH 3 and Naveen had a lower yield reduction under intermittent irrigation in both years (Table 5). Thus, these genotypes can be recommended for limited water-scarce areas.

Table 4. Impact of intermittent irrigation on phenology and physiology of rice.

Entry	50% flowering		Flag leaf area at flowering (cm^2)		Leaf relative water content % at flowering		Canopy temp. depression at flowering (C_t - C_a)	
	Normal	Intermittent	Normal	Intermittent	Normal	Intermittent	Normal	Intermittent
CO 49	103	99	30.4	26.9	87.8	85.1	9.2	6.1
CB 01 001	100	95	39.3	29.2	87.0	84.7	7.3	6.5
CB 05 501	90	87	32.0	27.5	85.6	82.9	8.4	5.6
Naveen	87	80	32.8	28.6	87.7	85.4	8.5	4.8
Triguna	92	89	29.1	23.9	86.2	83.6	8.2	7.2
CORH 3	85	83	33.9	30.3	89.7	87.4	8.0	5.3
PA-6201	95	91	31.9	26.1	88.0	83.4	9.6	6.2
PHB-71	93	85	30.5	24.9	89.2	83.9	8.1	7.5
	SED	CD at 5%	SED	CD at 5%	SED	CD at 5%	SED	CD at 5%
N	0.39	0.79	0.47	0.96	0.13	0.27	0.28	0.57
I	0.77	1.58	0.94	1.92	0.26	0.54	0.56	1.15
N x I	1.09	2.23	1.33	2.71	0.37	0.76	0.79	1.62

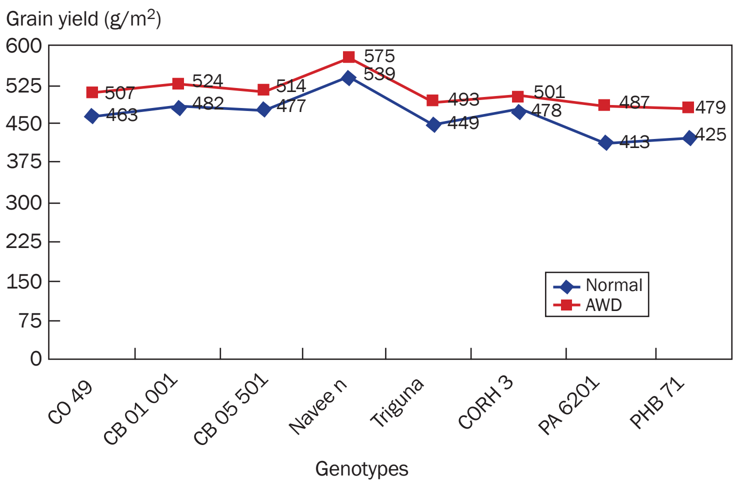

Fig. 2. Grain yield in g/m^2.

Conclusions

In conclusion, the results of our experiments conducted in both years of study (rabi 2007-08 and rabi 2008-09) were statistically significant. From these results, we can say that, by resorting to alternate wetting and drying to minimize the irrigation water requirement (at least one irrigation in a week), five to seven irrigations were saved, depending on the duration of rice genotypes, but with a cost of slightly lower yield components and grain yield.

Table 5. Percentage of yield reduction in rabi 2007-08 and rabi 2008-09 seasons.

Genotypes	% of yield reduction	
	2007-08	2008-09
CO 48	5.7	–
CO 49	–	8.7
Kr. Hamsa	11.6	–
CB 01 001	–	8.0
CB 05 501	–	7.1
MTU1010	12.7	–
Naveen	9.3	6.2
Triguna	–	9.0
CORH 3	6.2	4.5
PA-6201	15.2	15.0
PA-6444	8.9	–
PHB-71	9.0	11.4

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An economic analysis of hybrid rice technology in India

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Rice is the staple food crop of India, providing 30% of the calorie requirement for more than 70% of the Indian population. It occupies the highest area among the crops grown in the country. Within the country, rice is a major crop, accounting for 35.4% of the area and 42.9% of total food grain production and 43.5% of the area and 45.9% of total cereal production in the country, thus playing a pivotal role in the food and livelihood security of the people (Rani et al 2010). To meet the demand of the increasing population, current production of around 104 million tons (Agricultural Statistics at a glance 2012) needs to be increased to 122.1 million tons by 2020 (Kumar 1998). This increase in production has to be achieved in the backdrop of the declining and deteriorating resource base such as land, water, labor, and other inputs and without adversely affecting the quality of the environment. The task no doubt is quite challenging and the options available are limited in view of the plateauing trend of yield in high-productivity areas and decreasing and degrading land, water, labor, and other inputs. Among the various genetic approaches, hybrid rice technology is the most feasible and readily adoptable one. In this backdrop,we conducted a study to make an economic analysis of hybrid rice technology in India with the following objectives:

1. To compare the economics of inbred vs. hybrid rice cultivation.
2. To document the constraints to the adoption of hybrid rice technology.
3. To work out the economics of hybrid rice seed production.

Methodology

More than 80% of the total hybrid rice area of India is in eastern Indian states such as Uttar Pradesh, Jharkhand, Bihar, and Chhattisgarh, with a small area in Madhya Pradesh, Assam, Punjab, and Haryana (Hariprasad et al 2011). Hence, two important hybrid rice-producing states of eastern India, Uttar Pradesh, and Jharkhand, were selected for our study. Purposive sampling was followed to select the districts, blocks/*mandals*, villages, and farmers. Data were collected from four districts of two states—Ambedkarnagar and Bahraich districts of Uttar Pradesh and Khunti and Ranchi districts of Jharkhand. A sample size of 200 farmers was selected, of which 100 farmers were from Uttar Pradesh and 100 farmers were from Jharkhand, to compare the economics of inbred versus hybrid rice cultivation. Only those farmers who cultivated hybrid rice along with inbred rice varieties were included in the sample. The data on the economics of inbred and hybrid rice cultivation pertain to kharif 2010. To work out the economics of hybrid rice seed production, 100 farmers were selected from two districts (Warangal and Karimnagar) of Andhra Pradesh. The data on the economics of hybrid rice seed production pertain to rabi 2010. The primary data were collected from farmers through personal interviews according to a specially designed pretested schedule.

Results and discussion

The detailed cost of cultivation per hectare of inbred and hybrid rice was assessed based on the survey conducted and the results appear in Table 1. Table 1 shows that the total input costs per hectare of inbred rice cultivation were Rs.16,427 vis-à-vis Rs.19,502 for hybrid rice in Uttar Pradesh. Human labor use was more for hybrid rice cultivation than for inbred rice, which might be due to the extra management used by the sample farmers for hybrid rice as they purchase hybrid rice seed at a comparatively higher price than inbred rice seed. Among the variable costs for inbred rice cultivation, expenditures on fertilizer, manure, and seed accounted for 9.1%, 8.5%, and 5.7%, respectively. The major share in total input costs was accounted for by human labor in the cultivation of both inbred and hybrid rice (Fig.1). The expenditure incurred on seed was higher (14.3%) for hybrid rice than for inbred rice (5.7%). For hybrid rice, the expenditure incurred on fertilizer per hectare was comparatively high at Rs. 1,858 vis-à-vis Rs. 1,496 for inbred rice.

The total input costs incurred for cultivating inbred and hybrid rice in Jharkhand were Rs.13,017 and Rs. 16,463, respectively (Table 2). The expenditure for hybrid seed was more by two and a half times than that of inbred rice in both sample states. The expenditure for human labor accounted for a major share for both inbred and hybrid rice (Fig. 2) in Jharkhand also.

Table 1. Cost structure of inbred and hybrid rice cultivation (Rs./ha) in Uttar Pradesh.

Cost item	Inbred	Hybrid
Seed value	938	2,791
Farmyard manure value	1,399	1,560
Fertilizer	1,496	1,858
Irrigation	512	552
Plant Protection Chemicals (PPC)	640	679
Human labor	7,855	8,109
Bullock labor	966	1021
Machine labor	1,190	1,310
Miscellaneous	502	518
Interest on working capital	930	1,104
Total input costs	16,427	19,502

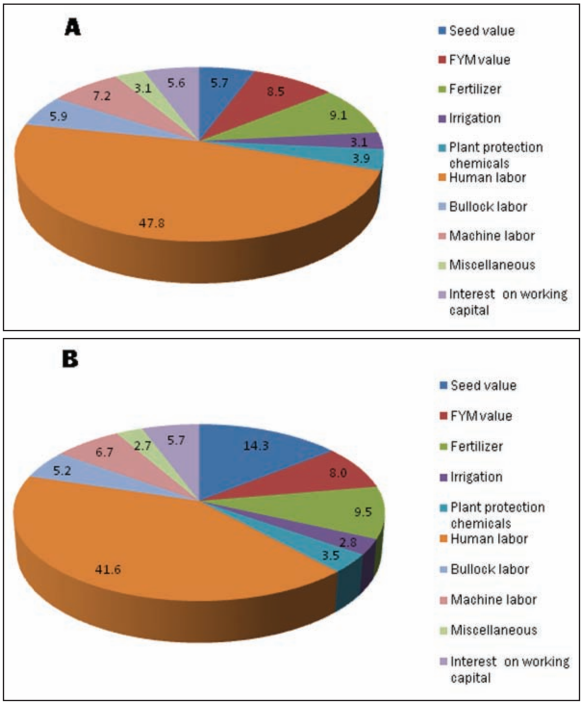

Fig. 1. Comparison of cost structure in inbred (A) and hybrid rice (B) cultivation in Uttar Pradesh.

Table 2. Cost structure of inbred and hybrid rice cultivation (Rs./ha) in Jharkhand.

Cost item	Inbred	Hybrid
Seed value	1,096	2,648
Farmyard manure value	1,300	1,310
Fertilizer	1,461	1,797
Irrigation	465	508
Plant Protection Chemicals (PPC)	558	650
Human labor	4,568	5,413
Bullock labor	1,158	1,174
Machine labor	1,347	1,597
Miscellaneous	328	436
Interest on working capital	736	932
Total input costs	13,017	16,463

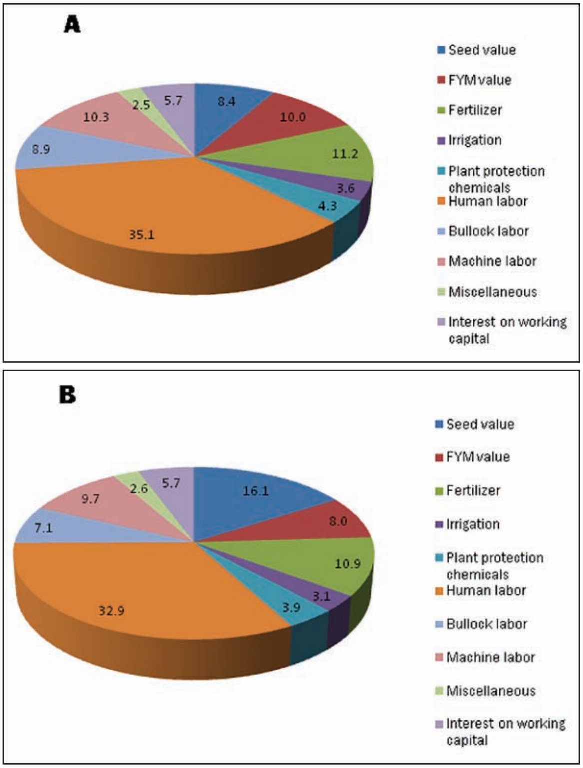

Fig. 2. Comparison of cost structure in inbred (A) and hybrid rice (B) cultivation in Jharkhand.

The average yield of inbred and hybrid rice in tons per hectare appears in Figure 3. It can be observed that the average yield of hybrid rice was higher than that of inbred rice in both states.The average yield of inbred rice in Uttar Pradesh was 4.5 t/ha, while hybrid rice yielded 5.7 t/ha. There was a yield increase of 26% for hybrid rice vis-à-vis inbred rice in Uttar Pradesh. In Jharkhand, the average yield was 2.5 t/ha and 3.8 t/ha, respectively, for inbred and hybrid rice. The yield gain due to the adoption of hybrid rice was 52% for Jharkhand. The other most important factor that determines the net profitability of hybrid rice cultivation is the market price of the final produce, which is an indicator of grain quality. Hybrid rice grain fetched a comparatively lower price than inbred rice in the market in the study area. Despite the comparatively low price obtained by the final produce of hybrid rice vis-à-vis inbred rice in both sample states, the cultivation of hybrid rice resulted in comparatively higher returns than inbred rice in both states. The gross returns obtained by hybrid rice were 12% and 31% higher than those of inbred rice in Uttar Pradesh and Jharkhand, respectively, mainly because of the yield advantage of hybrid rice over inbred rice (Fig. 4).

Janaiah (2002) reported a 16% higher yield for conventional high-yielding varieties of rice in India than for the cultivation of inbred varieties.

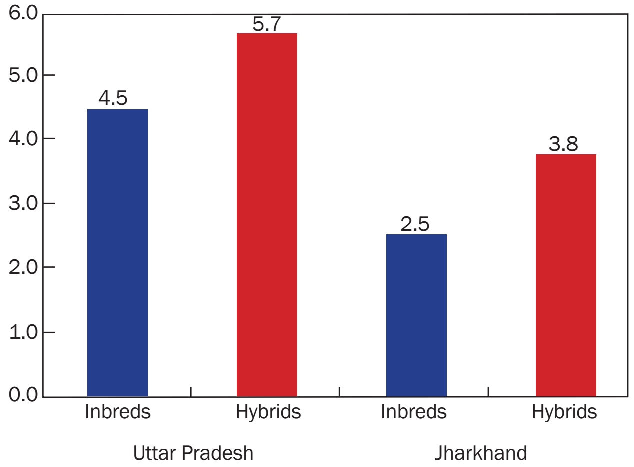

Fig. 3. Comparison of yields of inbreds and hybrids (t/ha).

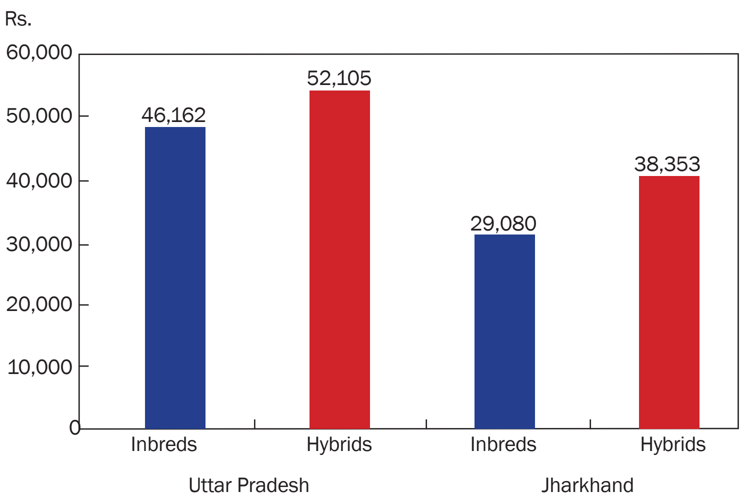

Fig. 4. Comparison of gross returns obtained by sample farmers for inbred and hybrid rice.

Data on farmers' perceptions regarding constraints to the cultivation of hybrid rice were collected. Garrett's ranking technique was employed to rank the constraints identified in cultivating hybrid rice. By using Garrett's formula, the percent position was obtained. Opinions were converted into scores by using Garrett's table. The mean score values were obtained and the constraints having the highest score were identified as the most important constraints.

Higher seed cost was the major constraint, with a Garrett score of 69.9, followed by lower pricing ability, poor cooking quality, lower profitability, and high management, with Garrett scores of 62.1, 54.9, 50.8, and 44.9, respectively, for Uttar Pradesh. Poor grain quality, high pest incidence, and higher grain shedding ranked sixth, seventh, and eighth with Garrett scores of 44.0, 42.5, and 42.2, respectively. The other constraints were low head rice recovery and lack of demand, with Garrett scores of 41.3 and 32.5, respectively.

Similarly, higher seed cost, lower pricing ability, poor grain quality, lower profitability, and poor cooking quality were the major constraints, with Garrett scores of 72, 67, 65, 59, and 54, respectively, in Jharkhand. High management, high pest and disease incidence, higher grain shedding, lower head rice recovery, and lack of demand were the other constraints to hybrid rice according to the opinion of the sample farmers.

The high cost of hybrid seed is one of the major constraints to the adoption of hybrid rice technology. This is primarily attributed to the low hybrid seed yield, which is around 2 t/ha. It is necessary to enhance seed yield to more than 2.5 t/ha in order to lower seed cost. Currently, hybrid rice seed production occurs in the rabi season, primarily in Warangal and Karimnagar districts of Andhra Pradesh. In this region, the seed is harvested by April-May, and, after drying, processing, testing, packaging, and transportation, it reaches northern India only by the beginning of June. As nursery sowing is done in this region by the end of May, the delay in the availability of hybrid seed affects the development of hybrid rice in northern India.

It can be observed from Figure 5 that total human labor charges accounted for the major share (26.5%) in both selected districts.Along with the normal operations involved in inbred rice cultivation, certain additional operations are involved in hybrid rice seed production. The additional human labor charges incurred in the additional operations in hybrid rice seed production accounted for 20%. The expenditure incurred on seed was meager and accounted for only 1% of the total input costs. Organic manure and fertilizer accounted for 6.6% and 9.1%, respectively. The expenditure incurred on plant protection chemicals accounted for 8.3%. The costs incurred for the application of gibberellic acid accounted for around 1% of the total input costs.

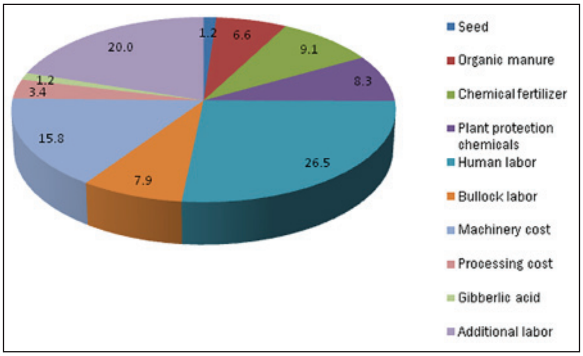

Fig. 5. Cost structure of hybrid rice seed production in Warangal and Karimnagar districts of Andhra Pradesh.

The average seed yield obtained by the sample farmers in Andhra Pradesh was 2,000.5 kg/ha. The price offered by seed companies for hybrid rice seed was around Rs. 51 per kg. The value of hybrid rice seed amounted to Rs. 102,085.5/ha. The average restorer yield was 1,868.25 kg/ha and the average price received by the sample farmers was Rs.7.22/kg. The value of restorer seed amounted to Rs.13,489/ha. Straw value was Rs. 3,127.5/ha. Total returns obtained from hybrid rice seed production were Rs. 118,701.8/ha.

Conclusions

Our study revealed that hybrid rice is economically superior, with additional gross returns ranging from 12% to 31% over those of inbred rice cultivation; hence, there is a need to increase the area under hybrid rice in the country in the coming years. The higher cost of seed was found to be a major constraint to the large-scale adoption of hybrid rice technology according tothe opinions of the sample farmers and hence the cost of hybrid seed should be reduced. This can be done by improving hybrid seed yield. Presently, about 80% of the hybrid seed requirement in the country is provided by two districts of Andhra Pradesh; hence, there is a need to identify potential areas for hybrid rice seed production. Hybrid rice has the potential to contribute significantly to improving production and food security. Therefore, efforts are needed to ensure the large-scale adoption of this technology.

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Notes

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The future impact of hybrid rice on food availability and affordability

Till Ludwig, Eric J. Wailes, and Alvaro Durand-Morat

World food prices spiked in 2007 and 2008, the largest spike since the world food crisis in 1972 and1973. Rice prices peaked in early 2008, with prices tripling in only a couple of months. In many countries, this led to surges in domestic retail prices of rice, affecting the food security of the population in those regions where rice is a staple crop. Lower income groups, whose incomes can barely cover food expenses, were especially hit hard with severe food insecurity. Although both the 1972-73 and 2007-08 food crises had similar effects on food security, the causes differed (Dawe 2010).

In addition to temporary shocks on food availability, agricultural production in general and rice production in particular face certain trends that need to be addressed. Three often-mentioned trends are demand growth, the limited availability of productive land, and climate change. The United Nations projects the world population to be 9.5 billion by 2050. The populations whose major staple crop is rice will increase by more than 1 billion. Moreover, the demand for agricultural products for alternative uses such as bio-energy is intensifying. Accordingly, it is estimated that the production of agricultural commodities needs to double in order to meet the additional demand (Trethowan et al 2010). Regarding rice production, though, estimates are more varying. Some projections estimate that rice production needs to increase only 5% up to 2020 (Timmer et al 2010) and others speak of 8% up to 2019 (Mohanty et al 2010). In any case, the increase in agricultural production is further challenged by the limited availability of agricultural land. Regarding rice production, there has been very limited extensification of agricultural land for the last 30 years. Deteriorating land quality and the use of agricultural land for other purposes have led the United States Department of Agriculture (USDA) to estimate that there will be a decline in area available for agricultural production (USDA 2010). Climate change is putting two main stresses on global agricultural activities: increased mean temperature and a higher probability of extreme weather events (Lobell and Burke 2010). On a global average basis, climate change will thus potentially lead to lower yield productivity and also to a higher risk of crop failure, which increases the risk of food crises.

These current trends emphasize the need for advancements in agriculture similar to the innovations that the Green Revolution achieved on a large scale. Hybrid breeding techniques were first applied by Yuan Longping in China during the 1970s (Li et al 2009). Different rice varieties with desired characteristics were crossbred systematically in order to produce hybrid varieties that contained the advantageous characteristics of their parents. Initially, hybrid rice research aimed to increase yield, though contemporary research is also looking for other aspects such as resistance to certain pests or higher input-use efficiency. In any case, progress in hybrid rice research has led to a higher average yield of rice plants. Hybrid rice varieties have become quite successful agricultural innovations so that their diffusion is relatively wide in some rice-producing countries compared with other agricultural innovations (e.g., more than a 60% adoption rate in China). Hybrid varieties, however, are not widely diffused, although in China their positive impact on food security cannot be denied. Nevertheless, diffusion rates can still improve and hybrid rice can still play a more vital role in securing food availability in other countries where rice is a major food staple. In regard to future trends, it could even be said that there is an obligation to mitigate future food risks in the best possible way in which hybrid rice is able to contribute more than today. If hybrid rice can affect food security positively, *how much* can hybrid rice contribute to future food availability? Can the advantages of hybrid rice deal with increasing demand solely or will there also be a need for other agricultural innovations in order to stabilize the global food situation? The objective of this study is to quantify what impact hybrid rice can have on future food security. We use the spatial partial equilibrium framework RICEFLOW to answer questions such as: What will be the future demand for rice? What will be the future supply of rice and what will be the price? What are the effects of continued hybrid rice adoption on production levels? What impact will a sustained and increasing adoption of hybrid rice have on food security? What are the benefits for consumers from the sustained and increasing adoption of hybrid rice? It can be expected that the demand for rice as well as the retail price will increase with population growth, which will be covered partially by an increase in production quantity, primarily due to yield advantages and input efficiencies of hybrid rice varieties.

About hybrid rice

Current deployment of hybrid rice

Considering the advantages and disadvantages of hybrid rice and possible impact on food availability, one could assume that, after more than three decades of research and development, hybrid rice technology would have become diffused on a large scale. In fact, the only country where hybrid rice is dominant is China. Qualitative research studies suggest that the disadvantages of hybrid rice prevail and cause farmers to hesitate to change from conventional to hybrid rice (Virmani et al 2003). It holds especially true that a developed hybrid rice variety cannot simply be adopted anywhere. The advantages of high-yielding varieties might therefore not be as large in different countries. On the other hand, the public sector seems to be aware of the advantages of hybrid rice and therefore pushes for hybrid rice research and development. Rice research and development are undertaken in many countries: Bangladesh, China, Egypt, India, Indonesia, Japan, Korea, Myanmar, the Philippines, Russia, Sri Lanka, Thailand, the U.S., Vietnam, and others (Virmani et al 2003). The major hybrid rice-producing countries, however, are much fewer.

China was the early adopter country of hybrid rice. Not only are the roots of hybrid rice there but it is also the country that achieved the highest diffusion rates of hybrid rice. According to recent reliable data, hybrid rice was produced on 18.6 million hectares in 2008, which accounted for 63% of the total rice area in China (Li et al 2009). This large deployment is comprehensible when seeing that the yield advantage of hybrid rice ranged from 17% to 53.2% between 1976 and 2008, which is on average a 30.8% higher yield than that of conventional varieties (Li et al 2009). Of all the hybrid rice varieties grown in China, 85% are indica rice and only 3% are japonica rice; the rest are a mixture of indica and japonica (Barclay 2010). However, for all commercially deployed hybrid rice varieties, it holds true that only long-grain varieties are produced on a large scale, whereas short- or medium-grain and fragrant hybrid varieties are being developed, but only rarely deployed. Other major hybrid rice-producing countries (according to area harvested) are mostly located in Asia as well, such as Bangladesh, India, Indonesia, the Philippines, and Vietnam. Outside of Asia, only the U.S. has relatively high adoption numbers (see Table 1).

Trends and future development of hybrid rice

Despite its high-yielding characteristic and its tendency for better adaptability to abiotic and biotic stresses, the adoption of hybrid rice has been delayed. Research and development require expensive and continuous investment through either public or private actors. At the farm level, the adoption of hybrid rice might present excessive financial or management constraints due to higher seed costs and different agricultural techniques that are needed. However, continued research is promising in

Table 1. Hybrid rice production in the major hybrid rice-producing countries (paddy rice equivalent).

Country	Hybrid rice (000 ha)	% of total rice area[d]	Total production of hybrid rice (000 t)	% of total rice production[f]
Bangladesh[a]	735	6.5	5,365	10.9
India[b]	1,500	3.3	9,000	7.5
Indonesia[c]	62	0.4	452	0.7
Philippines[a]	346	7.8	2,387	15.1
U.S.[c]	175	13.9	2,082	18.9
Vietnam[a]	645	8.7	3,508	8.8
Others[c]	100	–	–	–
Subtotal[d]	3,563	2.8	22,794	3.4
China[e]	18,600	63.2	141,360	71.7

[a]Figures for year 2008. Source: Janaiah and Xie (2010).
[b]Figures for 2011. Source: USDA (2012).
[c]Figures for year 2009. Source: Barclay (2010).
[d]Based on 2009 world area harvested without China. FAOSTAT.
[e]Figures for year 2008. Source: Li et al (2009).
[f]Based on 2010 data from FAOSTAT.

finding hybrid vigor that might be able to reduce adoption constraints and increase diffusion rates in the future. To do so, future hybrid vigor needs to adapt to social and environmental trends.

Perhaps the biggest challenge will be to produce a sufficiently large supply of rice in order to meet the growing demand at affordable prices. Not only will the world population likely grow by 2050 to 9.5 billion people, but the top 15 rice-producing countries will have a population increase from 4.2 billion to 4.7 billion by 2025 and to 5.3 billion people by 2050. Today's major hybrid rice-producing countries will have a population increase from 3.4 billion to 3.9 billion by 2025 and to 4.2 billion people by 2050 (see PRB 2011). Estimating naively the production increase needed to feed these additional people, today's rice production needs to increase 12% by 2025 and 26% by 2050. However, keeping substitutability of crops and other factors, such as negative income demand elasticites for rice in mind, current estimates as discussed above speak of the necessity of production increases between 5% and 8% by 2019-20 (Mohanty et al 2010, Timmer et al 2010). Currently, researchers, especially in China, are working on so-called "super" hybrids, which have a new one-way breeding method and are alledged to increase productivity by up to 60% compared with the classical three-line hybrids (Yuan 2004). China's roadmap for the large-scale diffusion of super hybrids aims for a date of 2015 (Li et al 2009), whereas currently only 20% of rice production consists of super hybrids (FAO 2010).

A second challenge that hybrid breeding technology has to deal with are abiotic stresses. Higher mean temperature and more extreme weather events are already prevalent. There can be positive and negative effects on crops associated with climate change. Some regions will experience a drier and hotter climate, putting pressure on crops and likely reducing crop productivity. Other regions, with more precipitation and higher temperatures, can expand agricultural production, especially in higher latitudes (Trethowan et al 2010). In total, though, crops will have a lower productivity, especially in those tropical geographic zones where rice is primarily grown. Other abiotic stress factors are unstable irrigation water reservoir systems (Napasintuwong 2009), soil erosion and degradation because of long-term chemical fertilizer applications (Li et al 2009), and less arable area in general will be available (USDA 2010). Some breeding strategies try to obtain hybrid varieties that can cope with the changing climate (Trethowan et al 2010); however, these hybrid varieties are yet to be commercialized.

Biotic stresses are a third trend that hybrid rice research addresses. Some hybrid varieties have seen reduced resistance to diseases and insects (Li et al 2009), though breeders are also continuously working on developing hybrids with multiple disease and insect resistance (Zhou et al 2008). In a nutshell, all this hybrid vigor in development is promising to improve food security in rice-consuming countries and to meet increasing demand.

Regarding these trends, a few quantitative studies have been conducted to estimate the impact of hybrid rice on food security (Durand-Morat et al 2011, Janaiah and Hossain 2003). Durand-Morat et al (2011) found that total global rice production would have been 2.3% lower in 2008 if hybrid rice adoption had not occurred. In China, as the major hybrid rice producer, rice prices would have been 14% higher, and in other countries rice prices would have been up to 3% higher. Moreover, they estimated that hybrid rice adoption rates had to increase up to 90% in the hybrid rice-producing countries by 2020 in order to maintain the same availability of rice per capita as in 2008. Other authors confirm that accelerated hybrid rice adoption can potentially help keep rice available and affordable (Janaiah and Hossain 2003, Xie and Hardy 2009).

Methodology

Methods

The overarching goal is to assess the potential impact of the larger-scale diffusion of hybrid rice on production, consumption, prices, and trade. It was shown above that hybrid rice characteristics can be manifold since research on new hybrid rice varieties is induced by various circumstances. Hybrid rice vigor can aim for drought tolerance, for insect resistance, or simply for improved yield. In any case, hybrid rice research aims to increase average yield compared with that of conventional rice under either similar conditions or certain changing stress situations. Consequently, a first prerequisite for the methods is that input and output characteristics of rice be represented.

More fundamentally, rice production itself is quite diverse. There is not only one rice variety, but there are short-, medium-, and long-grain varieties as well as fragrant rice. Neither is there only one processing step, but processing takes place from paddy rice to brown rice and to white rice for each rice variety and the processing steps vary in degree of bran removal, for example, lightly milled, well milled, etc. To make this more complex, each country has not only different rice consumption preferences but also different production and processing techniques. To have as complete a picture as possible of rice production and a comparable benchmark for hybrid rice production, all different rice varieties and processing steps will ideally be included in the framework of analysis.

Several countries are already producing hybrid rice. Policies and market forces might change this situation. In fact, the diffusion of hybrid rice is likely to change in the rice-producing countries. Thus, this research's methods take into account the microeconomic production of hybrid rice and aggregate this to the national production of affected countries.

This leads us to another prerequisite: external factors influence production on a large scale. As hybrid rice research is driven by changing environments, agricultural production in general is affected by changing environments. An earlier section mentioned that the increasing population would raise the demand for food products and for staple crops such as rice in particular. On the other hand, without yield improvements, decreasing land availability will limit agricultural production. Additional variables might also be taken into account; for instance, energy prices are likely to increase in the future for numerous reasons. Since the costs of fertilizer and mechanization are directly correlated to energy prices, this external factor must also be considered. An increase in available expenditure of households might lead to a change in diet, and hence to a different demand for rice. Therefore, household or per capita income is also an exogenous variable to consider. Furthermore, there might be products that can substitute for rice, such as wheat. Countless other external factors will affect rice production and will ideally be included in a complete framework.

Going from the country level to the global level, rice is an internationally traded commodity. Trade volumes are not as high as for other staple crops, but some countries depend to a large extent on rice imports or exports. Accordingly, trade will be considered in the framework as well.

Rice is a highly politicized commodity. Food security is a main reason for that, but also general bilateral and multilateral relationships contribute to this. Regarding global rice production, this is mostly reflected in trade policies and in governmental rice stocks. When talking about rice, free trade is an illusion. Nearly every country's trade policy includes tariffs, quotas, or other market-distorting techniques. These are adjusted constantly and can have tremendous effects on global rice production and consumption, as the last rice price spike in 2008 showed (Dawe 2010, Yu et al 2011). Rice stocks are usually accumulated in anticipation of market fluctuations, but, depending on a government's policy, stocks can actually also induce market fluctuations. For example, India's release of its huge stock of rice to the world market led to a drop in the rice price in 2011. This research will therefore also include policies and stocks in the framework.

Keeping those prerequisites in mind and considering the objective of this research—to reflect prices and quantities from a supply and demand framework, for production and consumption—some complexity is undeniable. A handful of agricultural economic models can satisfy the requirements at least partially: the Arkansas Global Rice Model (AGRM), the IRRI Global Rice Model (IGRM), AGLINK-COSIMO, the Country-Commodity Linked Modeling System (CCLS), and RICEFLOW (Adenäuer 2008, Durand-Morat and Wailes 2010, Matriz et al 2010, Wailes and Chavez 2011).

The RICEFLOW model

This study uses the RICEFLOW model, which was developed by Durand-Morat and Wailes (2010). It is written in GEMPACK (General Equilibrium Modeling Package), which is a modeling software suitable for computing general equilibrium models. The RICEFLOW model is a multiregion, multiproduct, spatial partial equilibrium framework for the global rice market, which was originally built on the basis of a spatial price equilibrium model of Takayama and Judge (1964) . Takayama and Judge's model could estimate regional trade flows of rice as a result of a transaction cost optimization problem. The original RICEFLOW model (Durand-Morat and Wailes 2003) required a careful calibration, which proved to be difficult and often led to compromises on the values of relevant parameters, a shortcoming that could be solved by adopting another modeling approach. The updated RICEFLOW model as it is used in this study (Durand-Morat and Wailes 2010) does not use the optimization approach but is solved by specifying behavioral equations according to neoclassical economic theory.

The disadvantages that accompany the updated modeling approach mainly consist of limits to create new bilateral trade flows and production. In other words, the current version of RICEFLOW allows for changes in existing markets but not the creation of new domestic markets and trade flows. The advantages in flexibility of specifications of demand and supply functions, as well as the incorporation of the Armington assumption, prevail for the purpose of this study.

Production is modeled as a composite two-stage budgeting process. The first stage determines the demand functions for intermediate composites and for value-added composites, whereas the second stage determines the demand for intermediate inputs and factors of production. The specification of production incorporates a number of independent technology variables related to the productivity of factors and inputs. The demand for intermediate and value-added composites is thus a function of activity level, technological characteristics of production, producer prices for activities, and the relative prices of each composite.

Substitution effects arising from relative changes in input prices are accounted for through the elasticity of substitution. Substitution can be set at zero (Leontief function), it can be unitary (Cobb-Douglas production function), or it can take any other value (constant elasticity of substitution function). This study specifies the production function as a Leontief function, thus allowing no substitution effect between factors and inputs. The use of the Leontief function can be justified to stress the impact of scarce resources. A limitation of resources (e.g., agricultural land) stresses the need for an intensification of agriculture but also limits its use. On the other hand, new technologies are created for substituting scarce resources (e.g., fertilizer for land). However, to emphasize the potential of hybrid rice in regard to a different input use as well as to a higher yield than conventional rice, the assumption of no substitution can be concise. Moreover, this scenario can be understood as a "worst-case scenario" (Durand-Morat et al 2011).

Primary inputs of labor and capital are specified as highly elastic, whereas the supply of land is highly inelastic. Intermediate inputs including fertilizers, pesticides, energy, and seeds are assumed to be perfectly elastic. Those elasticity specifications can describe the future situation for agricultural production adequately. This shows the limitation and importance of land and stresses that agricultural production does not allow a substitution of land in production, thus making intensification, as through hybrid rice varieties, necessary. Additionally, it allows for other innovations by stating substitution possibilities within other primary inputs and intermediate inputs. Finally, substitution between imported and domestically produced commodities is assumed to be unitarily elastic.

On the demand side, final consumption for each region is specified as a nonlinear function dependent on price and income. Price and income elasticities of demand are taken from the Food and Agricultural Policy Research Institute (FAPRI) based on the AGRM.

Two general system constraints are imposed on the model: market clearing conditions and zero-profit conditions. Market clearing conditions demand that all markets be cleared. This means in each case supply must equal demand. Included in the model are markets for input factors, for domestic commodities, and for composite commodities. All different stages of production are interrelated, and the market clearing conditions thus become increasingly important and complex to meet. Prices are the free variables that force markets to clear. In RICEFLOW, the factor supply is assumed to be exogenous.

The zero-profit conditions require that activities, wholesalers, or producers cannot receive extra profits. This condition is not a realistic criterion to reflect the real world but much more a necessity to create a clear correlation between prices and costs. Therefore, it means that prices reflect only the costs of factors of production and input costs and that no additional value is created during the production process. Under this condition, the model can display implications for consumer price changes when using a different technology much more than implying additional revenue potential for producers.

The most siginificant assumption of this study is the future adoption of hybrid rice (for more information, see Ludwig 2012). First of all, it has to be assumed that further adoption will indeed occur. Second, the rate of adoption needs to be estimated. The hybrid rice-producing countries are assumed to be further adopting hybrid rice according to specific S-shaped diffusion curves as outlined by Rogers (2003):

$$Yt = K[1 + e^{-(a+bt)}]^{-1}$$

The RICEFLOW model can be run in two ways, either deterministically or stochastically. A deterministic solution is based on the determined behavior of the model as it is set through the behavioral functions. These are specified by the elasticities, which accordingly form the core of the model. This implies that only variables and functions included in the model determine the solution and that no unpredictable factors are included. Accordingly, the deterministic solution reflects the model much more than a realistic image of the world. Nevertheless, if reality is explained by a significant amount of variables, the deterministic solution can be expected to be sufficiently close to the actual outcome.

The stochastic solution also relies on the variables and behavioral functions of the model, though in addition it assumes the influence of several unknown variables that are not included in the model but are nevertheless significant for the model's solution. Rather than giving an exact outcome, the stochastic solution will present a probabilistic result based on a known historical variability. The variability is mostly based on time-series data, when possible for each variable included in the model. The stochastic solution can also incorporate risk consideration of farmers on individual decision levels in regard to input factors or outputs, thus complicating the model further but also achieving more realistic projections. An application of the stochastic model can be found in Ludwig (2012).

In general, it can be said that the deterministic solution predicts a more or less exact tendency of the results, whereas the stochastic solution adds the probability to which the tendency might actually hold true. Since the deterministic solution is the basis for the stochastic solution, and since the model specifications are assumed to reflect reality accurately, this study will focus primarily on deterministic results and their interpretation.

A detailed description of the included variables, equations, and model specification can be found in Durand-Morat and Wailes (2010) and Ludwig (2012).

Data sources

The RICEFLOW model is a data-intensive model. To calibrate the model and the assumed scenarios, a baseline database needs to be created, which includes the characteristics of hybrid rice production in the observed countries. The scenarios differ from the baseline in the incorporation of population and expenditure increases as well as in the assumption that hybrid rice varieties are adopted in the observed countries in higher numbers than they are today. Thus, the scenarios will allow for a comparison of the projected results with regard to food security aspects between an impact scenario and a benchmark scenario.

The baseline for this research is calendar year 2009. The baseline is used to project values up to calendar year 2025. The year 2009 is used as the baseline because this year has the most recent and complete data available that are necessary for the model. The year 2009 also represents the first year after the latest rice price crisis with higher than average prices. In this special situation, the baseline data for that time can be seen as a challenged case scenario for rice market impact on food security; thus, 2009 is an appropriate baseline for calculating the impact of hybrid rice on food security. Projection data for expenditure growth and population increase allow for a mid-term outlook up to 2025. In general, it holds true that longer-term projections tend to become inexact, which could be reflected in the results of the modeled scenarios. Therefore, up to 2025 seems to be an appropriate timeframe. However, the results can be used as a trend to give educated guesses for the longer-term impacts of hybrid rice. Price data will be presented in U.S. dollars and data about volumes in metric tons.

The database used for this study contains 60 countries/regions for which reliable data could be found for the baseline year 2009. For the impact scenario of hybrid rice adoption, data for the seven major hybrid rice-producing countries are used.

The database is disaggregated in different activities and commodities. There are nine different product activities, which are primary production of three rice types (short and medium grain, long grain, and fragrant) and two milling stages for each rice type (paddy to brown rice and brown to fully milled white rice). Each commodity is created by an activity based on factors of production and intermediate inputs. The factors of production are land, labor, and capital. The intermediate inputs are included as exogenous commodities and consist of fertilizer, pesticides, energy, water, and seeds. The intermediate inputs are considered to be highly elastic; however, water is assumed to be highly inelastic.

Data for primary production come from the Food and Agriculture Organization of the United Nations' database (FAOSTAT). Primary production is disaggregated according to rice type based on information from the various ministries of agriculture. Data for bilateral trade for each rice commodity are acquired through the United Nations Commodity Trade Statistics Database (UN Comtrade). Data for rice inventories are found in the USDA PS&D database. Finally, stock changes are deducted from the yearly inventory; if no value is reported, no change in stocks is assumed.

The different processing activities and the composite commodities are derived in the following way. Domestic production of paddy rice is combined with imports and used as an input activity for the next processing step, dehusking to brown rice. Costs are included for dehusking/milling ranging from $25/t to $35/t depending on milling technology by country. The milling rate from paddy to brown rice is assumed to be 0.8.

The next processing step, bran removal and full polishing from brown rice to white rice, is similarly specified. Domestic production plus imports of brown rice is used as an input activity for the second milling stage. It uses milling rates, which are derived from USDA PS&D. The milling costs are assumed to range from $15/t to $20/t, again depending on the level of technology per region. The domestically produced white rice plus imported white rice minus exported white rice presents the final stock of white rice that is used for domestic consumption. Consumption data for calibration come from FAOSTAT and USDA PS&D.

For the hybrid rice impact scenario, production cost data for hybrid rice in each of the examined countries comes from various sources and case studies (Table 2).

These sources also reveal the advantages of hybrid varieties in terms of input use on an average basis for each region. The share of hybrid rice in total rice production was similarly gathered from various sources. All hybrid rice commercially produced is of the long-grain type, and its input-use advantage is embedded in the production costs of the regions currently producing it. Finally, rice production data are aggregated on a yearly basis for countries with double or tripple cropping systems.

Benchmark scenario and impact scenario

Starting from the baseline data, two principal scenarios are modeled and projected: a benchmark or status quo scenario as well as the hybrid rice impact scenario. The impact of higher hybrid rice adoption is then estimated as a difference from the benchmark scenario.

The benchmark scenario reflects a shock to the baseline results data only for the key exogenous variables of population growth and consumer expenditure in order to reflect the demand for rice up to 2025. The changes are applied to all regions of the baseline. Forecasts of population and expenditure growth rates are taken from the United Nations and World Bank, respectively. The benchmark scenario predicts an unrealistic but meaningful scenario, stating, if all else stays constant, what will be the impact of an increased population on rice production, demand, price, and other endogenous variables. In other words, the hypothesis can be tested: *In which way will the food security situation decline if additional hybrid rice varieties are not adopted?* This scenario is unrealistic since other variables are likely to change, too. However, it is still meaningful in depicting the food security situation under today's technology, thus creating a comparable benchmark for estimating the impact of hybrid rice technology.

The impact scenario differs from the benchmark scenario in that it further includes—above the assumptions of the benchmark scenario—the production cost and output advantages of expanding hybrid rice adoption in the examined countries. The impact scenario results can be used to test the hypothesis: *In which way does hybrid*

Table 2. Data sources for the modeled scenario.

Region	Data source	Year of data
Bangladesh	Hossain (2008)	2007
China	Li et al (2009)	2008
India	Janaiah and Xie (2010)	2008
Indonesia	Indonesian Center of Rice Research	2010
Philippines	Manalili et al (2008)	2008
U.S.	University of Arkansas (2011)	2011
Vietnam	Nguyen (2008), Pingali et al (1998)	2007, 1997

rice improve the food security situation under the same general conditions as the benchmark scenario? The results can indicate the potential of hybrid rice technology in regard to national or global food security.

Two variables were changed in order to reflect the impact of hybrid rice: the composition of production factors and yield of paddy rice. First, the diffusion of hybrid rice was estimated for the projected years. This was accomplished by applying an assumed diffusion curve on the area on which hybrid rice is grown, as outlined by Rogers (2003). On this basis, the production cost composition could be disaggregated for the baseline data and aggregated again for each projected year. Additionally, the yield of paddy rice in hybrid rice-producing countries could be estimated for each year. Although the advantages of hybrid rice heterosis can be manifold and the yield advantage of hybrid rice is likely to increase further in the future, only yield advantage and production cost efficiencies of current hybrid rice varieties were incorporated in the model. The relative differences between the production costs of hybrid rice varieties and conventional varieties are implemented proportionally according to the diffusion rate of hybrid rice per year.

Results

Table 3 compares the production changes of the benchmark scenario and of the impact scenario. To recall, the shift in the benchmark scenario is induced solely by population growth and increased expenditure, whereas the impact scenario also accounts for higher yields and production cost efficiencies due to hybrid rice adoption in the main hybrid rice-producing countries. The bold marked changes (Table 3) indicate the higher increase/smaller decrease in production in comparison to the 2009 baseline data. As can clearly be seen, the hybrid rice-producing countries are benefiting largely from the large-scale diffusion of hybrid rice in terms of production increases. Compared to no

Table 3. Comparison of production changes for LGP rice.

Country	Rice production					Hybrid rice difference from benchmark scenario to impact scenario (%)
		Benchmark scenario		Impact scenario		
	2009 (000 t)	2025 (000 t)	% change from 2009	2025 (000 t)	% change from 2009	
Bangladesh	47,723	55,094	15.44	56,443	**18.27**	2.45
China	170,705	166,396	**−2.53**	164,244	−3.79	−1.27
India	129,198	139,365	7.87	165,768	**28.31**	18.95
Indonesia	64,399	66,202	2.80	69,634	**8.13**	5.18
Philippines	16,266	17,866	9.84	20,535	**26.25**	14.94
U.S.	7,551	9,587	26.96	10,002	**32.46**	4.33
Vietnam	38,895	43,196	11.06	52,154	**34.09**	20.74
Total	474,738	530,957	4.84	538,779	**13.49**	1.47
Global	613,517	655,250	6.80	690,749	**12.59**	5.42

additional hybrid rice adoption, almost 38 million tons of LGP rice can be produced additionally by the seven countries. On the other hand, the global production of rice increases only by roughly an additional 36 million tons above the benchmark scenario. *This means that hybrid rice diffusion does produce more rice in absolute values, though the production is more concentrated in the hybrid rice-producing countries, making them more important in the global rice supply.*

China is the only exception to the otherwise clear results. China is actually producing less when hybrid rice adoption occurs. This can be explained by a shift in relative advantages between the rice-producing countries. China had a hybrid rice adoption rate of 63.2% in 2009. Higher diffusion rates of hybrid rice by 2025 make China's production more efficient, though, compared to countries such as the U.S., where, if hybrid rice adoption surges from 13.9%, the efficiency gains are relatively lower. The results in relatively higher production costs in China, eventually leading to increasing imports of rice and decreasing production of long-grain paddy.

Table 4 also draws a clear picture by illustrating the five countries that are most heavily dependent on rice as a staple food crop. In every case, a higher rice consumption can be achieved with hybrid rice adoption than without; the improvement ranges from 0.17% for Myanmar to 7.62% for Vietnam. However, in either scenario, rice consumption is decreasing. *In other words, hybrid rice diffusion can help to mitigate food insecurity, but this agricultural innovation cannot create complete food security on its own.*

A look at the retail price in Table 5 rounds out the picture. As before, we can see that hybrid rice adoption has a clear advantage for food security concerns. In every case, the impact scenario shows either a smaller increase in retail prices or even a decrease. Bangladesh and Vietnam show drastic changes between the two scenarios, indicating a higher use of rice in 2025 compared with the benchmark scenario. Bangladesh seems to be a special case, though. Looking at the rice consumption change, the improvement from the benchmark to impact scenario is not so large that the drastic decline in retail price can be explained. A partial explanation is that price elasticity is very low and rice consumption is saturated. Taking rice production additionally in consideration, it seems that there is a surplus production of rice in the impact scenario, which has a tremendous effect on the domestic retail price. Since Bangladesh is increasing its

Table 4. Comparison of rice consumption changes for LGW rice.

Country	Rice consumption					% change between scenarios
		Benchmark scenario		Impact scenario		
	2009 (kg/capita)	2025 (kg/capita)	% change from 2009	2025 (kg/capita)	% change from 2009	
Bangladesh	215.13	208.26	−3.19	210.02	−2.37	0.85
Cambodia	234.05	193.77	−17.21	194.61	−16.85	0.43
Laos	227.36	180.61	−20.56	184.22	−18.97	1.99
Myanmar	228.83	224.25	−2.00	224.64	−1.83	0.17
Vietnam	220.36	161.24	−26.83	173.53	−21.25	7.62

Table 5. Comparison of nominal retail price percent changes for LGW rice.

Country	Retail price changes for 2025 (%)		Hybrid rice difference from benchmark scenario to impact scenario
	Benchmark scenario	Impact scenario	
Bangladesh	127.34	−6.69	−134.03
Cambodia	3.27	1.04	−2.23
Laos	13.06	2.42	−10.64
Myanmar	179.79	174.89	−4.90
Vietnam	73.34	20.04	−53.3

production of rice by 15.5%, the tremendous effect on the retail price should be explained by the trade specifications. In 2009, Bangladesh imports 0.5 million tons of long-grain white rice (LGW) and exports no rice. By 2025, the imports increased for the benchmark scenario by almost 500%, to 2.48 million tons; additional production and imports cannot meet demand without a higher retail price. However, for the impact scenario, the imports decrease by 62.8% to 0.31 million tons. Keeping the limitation of the model specification in mind that no new trade flows can be created, and that Bangladesh will never export any rice, all the effects of the surplus production—and the indicated lower need for imports—are captured domestically; hence, retail prices decrease drastically.

Very strong effects of hybrid rice on food security also occur in Vietnam, as rice consumption increases, production increases, and the retail price declines by 53.3%. Cambodia has only a slight decrease in the retail price in the impact scenario, indicating a possible diet change; although more rice is available, demand does not increase; accordingly, the price is not increasing but exports expand. Myanmar seems to benefit only marginally from hybrid rice adoption. However, Myanmar is exporting rice in the 2009 baseline. In the benchmark scenario, exports decrease by 72.6% and in the impact scenario exports decrease by 88.1%. Thus, the impact scenario is increasing the volume of domestically commercialized rice and having a lesser impact on domestic retail prices in Myanmar. Finally, Laos' drop in retail prices due to hybrid rice adoption is sharp. *Nevertheless, the food supply and the largely positive effects on retail price show the advantages for food security.*

In summary, the discussion of the results of the most important countries clarifies that hybrid rice adoption has clear benefits in terms of food security aspects. *Production quantities increase globally, retail prices decline, and rice consumption increases.*

Conclusions

The objective of this study was to measure the impact of hybrid rice on food security. A positive effect of the diffusion of hybrid rice was expected, due to the advantages associated with hybrid rice. Hybrid heterosis can be summarized as higher yield, improved input efficiencies, and greater shock resistances than with conventional rice varieties. As Hayami and Ruttan (1985) imply, environmental conditions are the inducing factors for why hybrid varieties are developed. Regarding the global rice situation, growing demand, deteriorating agricultural land quality, and both abiotic and biotic stresses are the main aspects that are likely inducing research for new hybrid vigor. On the basis of Rogers (2003), the adoption and diffusion process of hybrid rice varieties was illustrated and this created the foundation for the assumed diffusion rates of hybrid rice until 2025, which could eventually trace the impact of hybrid rice on food security.

The spatial equilibrium model RICEFLOW was used for the quantification of the impact (Durand-Morat and Wailes 2010). RICEFLOW includes 60 regions and simulates the production processes, bilateral trade flows, and consumption patterns of different rice commodities. A benchmark scenario that included population and expenditure growth first projected the demand of rice and the according production and price changes. The impact scenario incorporated production and output characteristics of the assumed hybrid rice adoption in the seven major hybrid rice-producing countries. In comparison to the benchmark scenario, it could be shown that hybrid rice induces a 10.8% higher production of rice globally, and even a 12.1% higher production in the major hybrid rice-producing countries. The availability of rice is improved and this enhances rice consumption per capita between 0.17% and 7.62% in the countries that are most dependent on rice as a staple crop. It can be assumed that similar positive effects are also perceptible in other countries that depend on rice. Finally, the impacts on retail prices of LGW rice are important. However, because of imprecisions that are inherent to the model, the projection results cannot be taken literally, but as merely indicating trends.

This study can contribute to existing research in different ways. Regarding rice production in general, the estimation that global rice production will increase 5.6% by 2025 in the benchmark scenario is in line with other predictions on how much rice production will change under current agricultural technology (Mohanty et al 2010, Timmer et al 2010). The result, that further hybrid rice adoption will lead to even higher production in 2025, thus has positive effects on rice consumption and affordability, and also confirms the findings of different studies about the impact of hybrid rice on food security (Durand-Morat et al 2011, Li et al 2009). This study's results differ from findings that projected that hybrid rice adoption needs to increase up to 90% by 2020 in order to keep 2008 levels of rice availability per capita (Durand-Morat et al 2011). Neither at this level of hybrid rice adoption can rice consumption per capita be sustained, at least in the countries that are most dependent on rice as a staple crop; and, although projections for other countries were not specifically made in this study, the results indicate that this finding holds true also for other rice-consuming countries. Nevertheless, increased hybrid rice adoption can definitely help to keep rice affordable.

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