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Review Article

Super Hybrid Rice in China and India: Current Status and Future Prospects

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Abstract

Rice is a staple food for over half of the world's population and has the second largest cereal production after maize. Rice yield has experienced many fold jumps since the 1950s. This happened primarily as the result of genetic improvement and increasing harvest index by reducing plant height using the semi-dwarf genes and utilization of heterosis by producing hybrids. Hybrid rice technology is one of the strongest tools to break the yield barrier. To make hybrid rice technology practically feasible it needs strong system of hybrid seed production at commercial rate. Unlike maize, rice is a self-pollinated crop and needs special techniques, like utilization of male sterility system for hybrid seed production. The first hybrid rice variety for commercial cultivation was released by China in 1976. Seeing the China's success many countries started the hybrid rice breeding programme. India also started this programme in 1989. In about two decades of efforts India released 65 hybrid rice varieties till 2013. Though, China is cultivating about 50% of its rice area under hybrid rice varieties, India is still struggling to enhance its acreage under hybrid rice from 4% to more. Because of complicated seed production system, higher seed cost and less preferred qualities of hybrid varieties it could not cover more area under cultivation in India. In 1998, China started work for developing super hybrid rice by combining an ideotype approach with the use of inter-sub specific heterosis. Till 2011, the Ministry of Agriculture, China approved 56 hybrid cultivars with great yield potential as super hybrid rice. Hence, India and China still have to work hard for developing high yielding super hybrids coupled with good cooking qualities and resistance/tolerance to major biotic and abiotic stresses. Suitable technology should also be developed to make hybrid seed production easier and cheaper.

Keywords: *Oryza*; Hybrid rice; Male sterility; CGMS; TGMS; PGMS

Introduction

Rice (*Oryza sativa* L.) belongs to the genus *Oryza* of family Poaceae. The genus *Oryza* is known to consist of two cultivated species i.e. Asian rice (*O. sativa,* 2n=24=AA) and African rice (*O. glaberrima,* 2n=24=AA) and 22 wild species (2n=24, 48). About half of the world's population depends on rice for their survival. Rice is being cultivated in around 113 countries of the world. It contributes 19.62%, 24.63% and 40.52% of total food grain production of world, China and India respectively. In India, 56.68% of total rice area is grown on irrigated land, 27.21% on rainfed lowland and 5% on rainfed uplands (Rice Knowledge Management Portal, Hyderabad, 2012). India has the largest area under rice among the rice growing countries in the world and ranks second in production after China. India is one of the major rice export countries (22.7%) including Thailand (28%), Vietnam (24.5%), Pakistan (14%) and United States (10.8%). The major rice import countries are Nigeria (26%), Iran (22.5%), Philippines (17.3%), China (17.3%) and Indonesia (16.8%) (USDA 2012). The present world rice area, production and productivity is 158.93 mha, 465.03 mt and 4.36 t ha^{-1}, respectively. In India, it is being grown in 42.86 mha area with production of 104.32 mt and productivity of 3.59 t ha^{-1} and contributes 25% to agricultural GDP (Foreign Agriculture Services/USDA, Office of Global analysis, April 2012). To feed the ever growing population, the targeted rice production of the world, for the year 2030 is envisaged as 771.02 million tonnes (Alexandratos and Bruinsma, 2012). To get success in achieving the target, the increase in rice productivity is the only option left, since the other alternatives like cultivable land, water and other natural resources are either stagnant or declining (Yashitola *et al.,* 2002). Hence, there is an urgent need to boost the rice production through its enhanced productivity. Hybrid rice technology is one of the most important and practically feasible technologies to enhance the rice productivity. Like other crops, rice is also showing enough heterosis (15-25%) (Siddiq, 1997; Singh and Haque, 1999; Singh *et al*., 2013). Unlike maize, the hybrid seed production in rice is not possible without availability of strong male sterility system.

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A wild rice plant with aborted pollen in China's Hainan Island and the available fertility restorer genes in *indica* rice led the beginning of hybrid rice technology in 1970. The hybrid rice variety for commercial cultivation was released by China in 1976. Seeing the China's success many countries started hybrid rice breeding programme. India also started this programme in 1989. The study tours and fellowship trainings of a large number of Indian scientists in reputed institutes in China, IRRI, Philippines and in other countries helped in accelerating the hybrid rice research. In about two decades of extensive efforts, India has so far released 65 rice hybrids by both public and private sectors for commercial cultivation (Directorate of Rice Development Report, 2013, Patna). These hybrids have yield advantage of 1.0-1.5 t ha^{-1} over the highest yielding inbred varieties**.** During the year 2011, around 2 mha area was planted with hybrid rice in India. Hybrid rice is being cultivated predominantly in the states of Utter Pradesh, Jharkhand, Bihar, Punjab, Haryana, Madhya Pradesh and Chhattisgarh.

Some of the popular hybrids grown in the country are Arize-6444, PHB-71, KRH-2, PRH-10, PA 6129, Saihhadri, Suruchi, JKRH-2000, PAC 837 and DRRH-2. Other rice growing countries have also started hybrid rice research and its cultivation. Because of complicated seed production system, higher seed cost and less preferred qualities of hybrid rice varieties the enhancement in area coverage under hybrid rice in India is rather slow. Hence, proper strategies have to be adopted for research and development to overcome the above limitations to enhance hybrid rice acreage and ultimately to boost the rice production. The attempts have been made in super rice breeding in China and other countries in recent years. However, there were three main problems in super rice breeding: 1. the super rice varieties were still rare; 2. most super rice varieties exhibited narrow adaptability; and 3. current breeding theories emphasized too much on the rice growth model, but they were impractical in guidance for rice breeding. The super parent of hybrid rice should exhibit excellent performance in all agronomic traits, with the yield or sink capacity reached the level of the hybrid rice control in regional trials. The super hybrid rice combination should meet the following criteria: good rice quality, wide adaptation, lodging resistance, resistance to main insects and diseases, and the yield exceeded above 8% over the control varieties in the national and provincial regional trials. To achieve the goal, the technical strategies, such as selecting optimal combination of the parents, increasing selection pressure, paying more attention to harmony of ideal plant type, excellent physiological traits and all the agronomic traits, should be emphasized. The yield of seed production should reach 3.75 t ha^{-1} and 5.25 t ha^{-1} for the super hybrid rice combinations derived from early-season and middle-season types of male sterile lines, respectively (Chen *et al*., 2007).

Hybrid Rice Technology

Heterosis or hybrid vigour is regarded as superiority of F_1 hybrids over their parents and or over check varieties/hybrids. Heterosis is exploited through development of hybrids, synthetics and composites. In case of self pollinated crops like rice, synthetics and composites may not be used. Hence, to exploit heterosis in rice, development of high yielding hybrids is the only option where we may use full magnitude of available heterosis. To exploit the heterosis at commercial level it is necessary to have:

a. High magnitude of heterosis. Means, F_1 hybrid must show high economic heterosis.
b. Economical method of hybrid seed production.

Heterosis in Rice

Exploitation of heterosis was initiated in cross pollinated crops like maize, where inbreds exhibit inferior phenotypic performance due to inbreeding depression. Rice is a self-pollinated crop where pure lines are naturally formed with high phenotypic performance and little or no inbreeding depression. Although Jones (1926) was first to report existence of hybrid vigour in rice, progress in hybrid rice development was stalled due to two principal reasons, superior performance of pure lines and unavailability of suitable pollen control mechanisms.

In India, heterosis was first reported by Ramiah (1935) and Kadam *et al.* (1937). Being a self-pollinated crop with numerous bisexual flowers per inflorescence, hand emasculation for hybrid development is impractical in rice. Since, it is a self pollinated crop and farmers have to replace their seed every year, hybrid seed production at commercial scale is not possible without having a stable male sterility system. Therefore, by any means we have to make one of the parents as female to exploit it at commercial level. Hence, developing a suitable female parent is the major task to make hybrid rice technology practically feasible.

History of Hybrid Rice Technology in China and India

In 1964, Yuan Long Ping first put forward the idea of utilizing the heterosis in rice and initiated the research on hybrid rice in China.

- In1970, a pollen abortive wild rice plant (Wild Abortive; WA) was discovered among the plants of common wild rice at Nanhong Farm of Hainan Island of China and the available restorer genes in *indica* rice led the beginning of hybrid rice technology.
- In 1972, the first group of CMS lines such as *Zhenshan* 97A, V20A were developed by using WA as the donor of male sterile genes by way of successive backcrossing method.
- In 1976 - First commercial three-line rice hybrid released in China.

- In 1973 - PTGMS in rice was discovered in China.
- In 1994 - first commercial two-line rice hybrid released in China.
- In India- ICAR launched a mission mode project on hybrid rice in December, 1989.
- IRRI, Philippines collaborated with the project by providing the needed germplasm and technical support. This project was further strengthened with financial support from UNDP and technical support from FAO since September, 1991-1996.
- Mahyco Research Foundation (MRF), now popularly known as Barwale Foundation provided financial assistance to the hybrid rice project during 1996-2002 to fill critical gaps, which is a good example wherein a private foundation supported a public sector research.
- In 1994 first time hybrid rice (APHR1, APHR2, MGR1 and KRH1) were released in India.
- The research network consists of 12 active research centers across the country each with a specific mandate. India released 65 hybrid rice varieties till 2013 (Table 1).

The History of Super-Hybrid Rice Breeding

In 1982, the Japanese government initiated super high yielding rice breeding program. China and some other countries have paid great attention to super high-yielding rice breeding. The target was to achieve the yield of the brown rice output to 7 500 - 9 800 kg ha^{-1} in the medium and low yield areas, and over 10, 000 kg ha^{-1} in the high yield areas, to increase rice yield by 50% than control varieties in 15 years, by breeding high-yielding rice varieties and by developing the corresponding cultivation technology. Rice varieties such as Akenohoshi and Akichikara, which achieved nearly 10 000 kg ha^{-1} in the high yield areas, were developed at several breeding stations in Japan in the later eight years. However, these varieties were not being extended in large areas due to the lack of cold resistance, poor grain quality and low seed setting rate.

To break the yield barrier, scientists at the International Rice Research Institute (IRRI) proposed the plan of breeding 'new plant type rice' (also called 'super rice') in 1989. The goal was to breed new rice varieties with the yield potential of 13 000 - 15 000 kg ha^{-1} and increase of 20-30% than the control varieties. However, due to low biomass production, poor grain filling, low seed setting rate and susceptibility to diseases and insects, the new varieties have not been released for rice production in farmers' fields.

The China's super rice project was started in 1996. By the cooperation of nationwide breeders and researchers of China more than 20 super rice varieties or hybrid rice combinations such as Liangyoupeijiu and Xieyou 9308 were bred. The yields of these varieties or hybrids were higher than 10.5 t ha^{-1} in larger planted areas, and increased by 15% comparing to the hybrid rice combinations widely planted at present in China. The new hybrid rice combinations were also called 'super hybrid rice', which stood for the success of super rice breeding in China (Chen *et al*. 2000; 2007).

The Strategies for Super Hybrid Rice Breeding

The main strategies for breeding super hybrid rice combinations with wide adaptability, high yield potential, good rice quality and multiple disease and insect resistances are to combine the ideal plant type with physiological vigor and to harmonize all the growth traits, by improving the selective pressure on the basis of crosses from the super parents. Firstly, optimal combination of the parents is one of the key strategies for hybrid rice breeding. Optimal combination means that the hybrid rice combination derived from the parents with a reasonable genetic difference, such as from (1) lowland rice and upland rice varieties, (2) different varieties with geographically remote distance, (3) different ecological types, (4) different dominant varieties, and (5) indica and japonica (Cheng *et al.,* 2007). However, what needs to be emphasized in particular is that we can exploit only part of the heterosis between the indica and japonica subspecies, but not the heterosis between the typical indica and japonica rice or the one including excessive indica and japonica ingredients. Generally, the hybrid rice crossed from typical indica and japonica rice would result in the poor adaptability and stability of seed setting rate. Secondly, maintaining high harmony in a great degree of plant type, leaf shape, yield components and physiological function is another key strategy of super hybrid rice breeding. Increasing selection pressure is the third important strategy for breeding super hybrid rice with wide adaptability. For some important traits, such as resistance to higher or lower temperatures and rice blast, and the sterility of T(P)GMS and CMS lines, we usually grow the candidate plants in the conditions where it is easy to identify these traits. The super hybrid rice will be more vigorous and competitive only when bred under the conditions with added selection pressure. However, the breeding efficiency will be improved greatly after pyramiding multi-resistance and other favourable genes into the super hybrid rice parents by using the molecular breeding technology (Chen *et al*., 2007).

Problems and Prospects in Super Hybrid Rice Breeding

Since launching the project of 'super rice breeding' in China in 1996, great achievements in super rice breeding have been acquired in ten years. However, we should be well aware of the super rice varieties which are still rare, especially for growing in double-cropping rice regions in southern China. In addition, most of the currently super hybrid rice combinations have low seed setting rate, poor yield stability and weak adaptability, caused by their genetic disharmonies. These problems have been the factors

inhibiting extension of these super rice varieties to the large area. On the other hand, with the increasing in yield of the new rice varieties and level of breeding strategy, the theories of super high-yielding breeding have to be further improved. Exploitation of *indica*/*japonica* heterosis can heighten the level of yield. With the development of molecular marker technology in rice, the subspecies differentiation of parents can be determined and the proper contribution of *indica* and *japonica* genes in hybrids can be established for high yields in combination with harmonious plant types. Molecular marker-assisted selection has provided an approach to pyramid beneficial alleles of QTLs for improving yield and other important traits. Recently, some restorer lines carrying beneficial alleles of yield QTLs and major genes for disease resistance are under evaluation in the super hybrid rice breeding program. Incorporation of the characteristics of high photosynthetic rate from other species into rice plants is of importance for future super hybrid rice breeding (Chen *et al*. 2007).

Techniques of Hybrid Rice Seed Production

Since rice is a self pollinated crop, one of the parents to be used as female must be made male sterile through proper technique. Several types of techniques for making female may be tested and developed for hybrid seed production are:

Cytoplasmic Genetic Male Sterility (CGMS), also known as three line system.

Environmental sensitive Genetic Male Sterility (EGMS), also known as two line system.

Apomixis, also known as One Line System.

Chemically Induced Male Sterility (CIMS).

CGMS System (3-Line System for Hybrid Seed Production)

In India, this system is being used for hybrid rice seed production at a commercial scale. No other system is being used commercially in this country. However, China first started using this system at a commercial scale but now is focusing towards EGMS systems for hybrid rice seed production apart from CGMS systems. Since in CGMS system, 3 lines *viz.,* 'A' line (CMS line), 'B' line (maintainer line) and 'R' line (Restorer line) are needed every year therefore this system is designated as 3-line system of hybrid seed production. The cytoplasmic-genetic male sterility (CGMS) system is the result of interaction between specific sterility inducing cytoplasm and the nuclear gene(s). To get male sterility expression both sterile cytoplasm and recessive (*rf*) nuclear genes are required. Hence, it becomes necessary to identify several male sterile sources in rice. As in China, the WA type of CMS source was developed, the other sources are also to be developed for diversification of genetic materials to exploit usable heterosis. Some of the promising CMS lines developed in India are listed in Table 2.

'A' Line (CMS line): It is a female parent being used for the purpose of hybrid seed production. It has male sterile gene (S) in its cytoplasm. As rice flowers are bisexual hence, it is not possible to use normal parents as female by hand emasculation at commercial scale. Therefore, it is necessary to have a female parent as cytoplasmic male sterile (CMS line). Since, it is a CMS system, male sterility inheritance will be of maternal type. This results the F_1 hybrid to be sterile if the male parent being used is not having the dominant restorer gene (*Rf* gene) in its nucleus. Hence, it is necessary to have 'R' line as a male parent for producing hybrid rice seed (Fig. 1).

'R' Line (Restorer Line): This parent is being used as male parent for hybrid rice seed production. As it has restorer gene(s) (*Rf* gene) in its nucleus when it is hybridized with 'A' line then the hybrid seed produced on 'A' lines will have the fertility restorer gene in its nucleus in heterozygous condition (Rf_1rf_1). Hence, these hybrid seeds will be fertile which will be used by the farmers for hybrid rice crop cultivation (Fig. 2).

'B' Line (Maintainer Line): It is the isogenic of 'A' line and being maintained every year only for maintaining the 'A' lines (Fig. 3).

Maintenance of Parental Lines (A, B and R lines)

Since, 'B' and 'R' lines are normal inbred lines hence their maintenance needs not require any special techniques. These are being maintained in a similar manner as other inbred rice varieties are being maintained in isolation. Hence, maintenance of only 'A' line requires special techniques.

Maintenance of 'A' line: It is generally observed that 'A' lines are late in flowering than to their respective 'B' lines by 3-5 days. Therefore, it is necessary to have staggered sowing of 'A' and 'B' lines to synchronize the flowering of both. Hence, in seed beds, 'A' lines are sown 3-5 days earlier than 'B' lines. Generally, 21-25 days old seedlings are transplanted in the field. The maintenance field of 'A' line should have an isolation distance of 400 m and 200 m for breeder and foundation seed production respectively from the other plots to avoid unwanted pollen contamination to 'A' line.

Transplanting of 'A' line and 'B' lines should be done in such a way that helps more and more pollen dispersal from 'B' line to 'A' line to enhance higher seed setting in 'A' line, which will be used for hybrid seed production in next year. The row ratio of 'B' line and 'A' line is generally kept at 2: 4 or 2: 6. To help pollen dispersal, generally 'stick' shaking or 'rope' shaking is done once or twice daily at the time of peak anthesis. Plant and row spacing should be adjusted as per the agro-climatic conditions being used in rice cultivation.

Special supervision should be taken for avoiding off type plants. Hence, regular roguing must be done to remove all the off type plants from 'A' as well as from 'B' lines.

Table 1: Hybrid Rice Released in India

S. No.	Rice Hybrids	Year of release	Duration (Days)	Yield (tha^{-1})	Developed by	Recommended for
1.	APHR 1	1994	130-135	7.14	APRRI, Maruteru (ANGRAU), Hyderabad	Andhra Pradesh
2.	APHR 2	1994	120-125	7.52	APRRI, Maruteru (ANGRAU), Hyderabad	Andhra Pradesh
3.	MGR 1	1994	110-115	6.08	TNAU, Coimbatore	Tamil Nadu
4.	KRH 1	1994	120-125	6.02	VC Farm , Mandya, UAS, Bangalore	Karnataka
5.	CNRH 3	1995	125-130	7.49	RRS, Chinsurah (W.B.)	West Bengal
6.	DRRH 1	1996	125-130	7.30	DRR, Hyderabad	Andhra Pradesh
7.	KRH 2	1996	130-135	7.40	VC Farm , Mandya, UAS, Bangalore	Bihar, Karnataka, Tamil Nadu, Tripura, Maharashtra, Haryana, Uttarakhand, Orrisa, West Bengal, Pondicherry and Rajsthan
8.	Pant SankarDhan 1	1997	115-120	6.80	GBPUAT & T, Pantnagar	Uttar Pradesh
9.	PHB 71	1997	130-135	7.86	Pioneer Overseas Corporation, Hyderabad	Haryana, U.P., Tamil Nadu, Andhra Pradesh, Karnatka
10.	CORH 2	1999	120-125	6.25	TNAU, Coimbatore	Tamil Nadu
11.	ADTRH 1	1999	115-120	7.10	TNRRI, Aduthurai (TNAU)	Tamil Nadu
12.	Sahyadri	1998	125-130	6.64	RARS, Karjat (BSKKV)	Maharashtra
13.	NarendraSankarDhan 2	1998	125-130	6.15	NDUAT & T, Faizabad	Uttar Pradesh
14.	PA 6201	2000	125-130	6.20	Bayer Bio-Science, Hyderabad	Andhra Pradesh, Karnataka, Bihar, Orissa, Madhya Pradesh, Uttar Pradesh, West Bengal,Tamil Nadu and Tripura
15.	PA 6444	2001	135-140	6.11	Bayer Bio-Science, Hyderabad	U. P., Tripura, Odisha, Andhra Pradesh, Karnataka, Maharashtra, Uttarakhand
16.	Pusa RH 10	2001	120-125	4.35	IARI, New Delhi	Haryana, Delhi, Western U.P. and Uttarakhand
17.	PRH-122R (Ganga)	2001	130	5.64	Paras Extra Growth Seeds Ltd., Hyderabad	Bihar, Orissa, Punjab, U.P., Uttarakhand, Nagaland, Haryana
18.	RH 204	2003	120-126	6.89	Parry Monsanto Seeds Ltd., Bangalore	Andhra Pradesh, Karnataka, Tamil Nadu, Haryana, Uttarakhand and Rajsthan
19.	Suruchi 5401	2004	130-135	5.94	Mahyco Ltd., Aurangabad	Haryana, Andhra Pradesh, Karnataka, Gujarat, Odisha, Chattishgarh and Maharashtra
20.	Pant SankarDhan 3	2004	125-130	6.12	GBPUAT & T, Pantnagar	Uttarakhand
21.	Narendra Usar Sankar Dhan 3	2005	130-135	5.15	NDUAT & T, Faizabad	Saline & alkaline areas of U.P.
22.	DRRH 2	2005	112-116	5.35	DRR, Hyderabad	Haryana, Uttarakhand, W.B and Tamil Nadu
23.	Rajlakshmi (CRHR 5)	2005	130-135	5.84	CRRI, Cuttack	Boro areas of Aasam,Orissa
24.	Ajay (CRHR 7)	2005	130-135	6.07	CRRI, Cuttack	Irrigated areas of Orissa
25.	Sahyadri 2	2005	115-120	6.50	RARS, Karjat (BSKKV)	Maharashtra
26.	Sahyadri 3	2005	125-130	7.5	RARS, Karjat (BSKKV)	Maharashtra
27.	HKRH-1	2006	139	9.41	RARS,Karnal (CCSHAU)	Haryana
28.	CORH-3	2006	115	-	TNAU, Coimbatore	Tamil Nadu
29.	JKRH 401	2006	125	6.22	JK Agri. Genetics Ltd. Hyderabad	Bihar, Odisha, W.B.
30.	KJTRH 2	2006	N.A.	N.A.	RARS, Karjat (BSKKV)	Maharashtra
31.	Haryana Shankar Dhan-1 (HKRH-1)	2006	139	9.40	HAU, Haryana RARS,Kaul(CCS,HAU.)	Haryana
32.	HRI-152 (IET 18815)	2007	120 (Mid early)	NA	Bayer Bio-Science, Hyderabad	Punjab & Tamil Nadu
33.	JRH-4	2007	110-115	7.50	JNKVV, Jabalpur	Madhya Pradesh
34.	JRH-5	2007	105-108	7.50	JNKVV, Jabalpur	Madhya Pradesh
35.	Indira Sona	2007	120-125	7.0	IGKKV, Raipur	Chhattisgarh
36.	PA 6129	2007	115-120	6.58	Bayer Bio-Science, Hyderabad	Punjab, Tamil Nadu, Pondichery
37.	GK -5003	2008	128	6.04	Ganga Kaveri Seeds Pvt. Ltd., Hyderabad	Andhra Pradesh, Karnataka
38.	Sahyadri - 4	2008	115-120	6.80	RARS, Karjat (BSKKV)	Haryana, W. B., Maharashtra, U.P. and Punjab
39.	JRH- 8	2008	105-110	7.50	JNKVV, Jabalpur	Madhya Pradesh
40.	DRH - 775	2009	97	7.70	Methelix Life Sciences, Pvt. Ltd. Hyderabad.	Chhattisgarh, Jharkhand, West Bengal
41.	HRI -157 (IET 19511, 91H97226) (Arize Prima)	2009	130-135	6.50	Bayer Bio-Science, Hyderabad	Chhattisgarh, Gujarat, Bihar, Jharkhand, Odisha, Maharashtra, A.P.,T.N. Karnataka, Madhya Pradesh, Uttar Pradesh, Tripura
42.	PAC 835 (PAC 80035) (IET 18178) Hybrid	2009	130	5.60	Advanta India Ltd., Hyderabad	Odisha, Gujarat
43.	PAC 837 (PAC 80037) (IET 19746) Hybrid	2009	130	6.30	Advanta India Ltd., Hyderabad	Gujarat, Chhattisgarh, J&K, Andhra Pradesh, Karnataka
44.	NK - 5251	2009	128	6.65	Syngenta India Ltd., Secundrabad	Andhra Pradesh, Gujarat, Karnataka, Maharashtra, Tamil Nadu
45.	DRRH- 3	2009	131	6.07	DRR, Hyderabad	Andhra Pradesh, Gujarat, Madhya Pradesh, Odisha, U.P.

continued

Table 1: Continued

46.	US - 312	2010	125-130	5.76	Seed Works International, Hyderabad.	Andhra Pradesh , Bihar , Karnataka, Tamil Nadu, Uttar Pradesh, W. B.
47	CRHR-32	2010	125	5.43	CRRI, Cuttack, Odisha	Bihar, Gujarat
48	INDAM 200-017	2010	120-125	6.60	Indo-American seeds, Hyderabad	Odisha, Chattishgarh, Gujarat Maharashtra, A.P.
49	27P11	2010	115-120	5.67	PHI Seeds(P) Ltd.	Karnataka, Maharashtra
50	VNR 2245 (IET 20716) (VNR-204)	2011	90-95	6.83	VNR Seeds Pvt. Ltd., Raipur-492099	Chhattisgarh, Tamil Nadu
51	VNR 2245 (IET 20735) (VNR-202)	2011	100-105	5.75	VNR Seeds Pvt. Ltd., Raipur-492099	Uttar Pradesh, Uttarakhand, West Bengal, Maharashtra, Tamil Nadu
52	Shyadri-5 (Hybrid)	2011	110-115	NA	RARS, Karjat (BSKKV)	Konkan Region of Maharashtra
53	CO (R) H-4	2011	130-135	7.34	TNAU, Coimbatore	Tamil Nadu
54	Hybrid CO 4	2012	130-145	7.34	NA	Tamil Nadu
55	US 382 (IET 20727)	2012	125-130	6.70	Seed Works International Pvt. Ltd., Hyderabad-34.	Tripura, Madhya Pradesh, Karnataka
56	27P31 (IET 21415)	2012	125-130	8.0-.9.0	PHI Seeds Pvt. Ltd. Hyderabad- 82.	Jharkhand, Maharashtra, Karnataka, Tamil Nadu
57	27P61 (IET 21447)	2012	132	6.70	PHI Seeds Pvt. Ltd. Hyderabad- 82.	Chhattisgarh, , Gujarat, Andhra Pradesh, Karnataka,Tamilnadu
58	25P25 (IET 21401)	2012	110	6.70	PHI Seeds Pvt. Ltd. Hyderabad- 82.	Uttarakhand, Jharkhand, Karnataka
59	ArizeTej (HRI 169) (IET 21411)	2012	125	70.0	Bayer Bio Science Pvt. Ltd, Hyderabad – 81.	Bihar, Chhattisgarh, Gujarat, Andhra Pradesh, Tamil Nadu
60	PNPH 24 (IET 21406)	2012	120-130	NA	Nuziveedu Seeds Limited, Medchal Mandal, Ranga Reddy- 501401 (A.P.)	Bihar, West Bengal, Odisha
61	PNPH 924-1 (IET 21255)	2012	125-135	NA	Nuziveedu Seeds Limited, Medchal Mandal, Ranga Reddy- 501401 (A.P.)	West Bengal, Assam
62	NK 5251 (IET 19738)	2012	NA	NA	NA	Tamil Nadu, Karnataka, Andhra Pradesh, Maharashtra, Gujarat
63	JKRH 3333 (IET 20759)	2013	135-140	5.98	JK Agri Genetics Ltd, Hyderabad- 16.	West Bengal, Bihar, Chhattisgarh, Gujarat, Andhra Pradesh
64	RH- 1531(Frontline Gold) (IET 21404)	2013	118-125	NA	Devgen Seeds & Crop Technology, Hyderabad	Major Hybrid rice growing regions (Madhya Pradesh, Uttar Pradesh, Andhra Pradesh, Karnataka, Maharashtra)
65	CO 4 (IET 21449) (TNRH 174)	2013	NA	NA	TNAU, Coimbatore	Tamil Nadu, Gujarat, Maharashtra

Source: Directorate of Rice Development, Patna (2013), India

Table 2: Promising CMS lines developed in India

Centre Promising	CMS lines developed
DRR, Hyderabad	DRR 6A, 9A, 10A, 12A, 14A, 15A
IARI, New Delhi	Pusa 3A, 4A, 5A, 6A, 10A, 11A
PAU, Ludhiana	PMS 3A, 10A, 12A, 17A
RARS, Karjat	KJTCMS 1A, 2A, 3A, 4A
ARS, Ratnagiri	RTN 8A, 10A, 13A, 14A
APRRI, Maruteru	APMS 6A, 8A, 9A
CRRI, Cuttack	CRMS 32A, CRMS 31A

Source: Rice Knowledge Management Portal, DRR, Hyderabad, India

Table 3: Some Important Sources of Male Sterility Inducing Cytoplasm in Rice

Designation	Cytoplasmic source	First nuclear donor
CMS-WA	Wild rice with abortive pollen	Zhen shan 97 V20, V41
CMS-DA	Dwarf wild rice with abortive pollen	Xue Qin Zhao
CMS-IP	Indonasian paddy	II-32
CMS-DT	Dissi type	297
CMS-HL	Hong lian	Lian – Tana Chao
CMS-KR	*Oryzarufipogon*	Taichung 65
CMS-BT	Chinsurahboro II	Taichung 65
CMS-TN	TN 1	Pankhari 203
CMS-GAM	*Gambiaca*	Chao yang 1
CMS-ARC	Assam rice collection IRRI Acc-13829	IR 10179-3-2-1
CMS- *O. perennis*	*O. perennis*, Acc. 104823	IR 64R

Source: Rice Knowledge Management Portal, DRR, Hyderabad, India

Particular attention should also be given for roguing of pollen shedder plants observed in 'A' lines. All recommended agronomic practices should be adopted for raising good crop. At maturity, 'B' lines should be harvested first and should not be used for seed production. This will avoid mixing of seeds from 'B' line to 'A' line. Later 'A' line is harvested, threshed, dried and stored properly to use it in next year for hybrid seed production (Fig. 4). Some important sources of male sterility inducing cytoplasm in rice are listed in Table 3.

Hybrid Seed Production

This is done at certified seed level. Till foundation seed level, only parental lines are multiplied. For hybrid seed production, 'A' line and 'R' line are used and seeds harvested from 'A' lines will be the F_1 hybrid seed (Fig. 5).

EGMS System (2 Line System of Hybrid Seed Production)

A new kind of genetic male sterility i.e. Environment Sensitive Genic Male Sterility has been deployed for developing commercial hybrids particularly in rice. In this system, male sterility condition is due to the interaction of nuclear genes with environmental factors such as photoperiod, temperature or both. Hybrid seed production through two line system is simpler if it becomes feasible. Magnitude of heterosis in two-line hybrids is usually 5 to 10% higher than in three line hybrids because of no cytoplasmic penalty. The EGMS comprises of the following three types.

PGMS (Photoperiod Sensitive Genic Male Sterility)

It was discovered as spontaneous mutation in *japonica* cultivar Nongken 58 in China. It includes genic male sterile lines which respond to the photoperiod or duration of day length for expression of pollen sterility and fertility behavior. Most of the PGMS lines remain male sterile under a long day (>14 h) condition and revert back to fertility under short day (<13.5 h) condition.

TGMS (Thermo Sensitive Genic Male Sterile Lines)

It was discovered by Zhao *et al.* (1988) as spontaneous mutation in China. Male sterility/fertility alteration is conditioned by different temperature regimes. Most of the TGMS lines remain male sterile at a high temperature (Max. > 30°C) and they revert back to partial fertility at a lower temperature (< 30°C). The critical sterility/fertility points vary from genotype to genotypes. The critical thermo sensitive stage for fertility alteration in TGMS line varied from 15-25 days before heading and 5-15 days after panicle initiation.

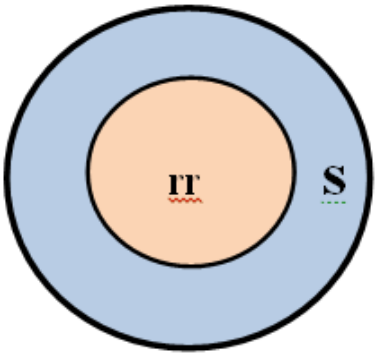

Fig. 1: 'A' line (CMS line)

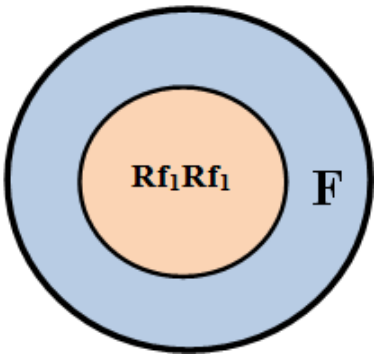

Fig. 2: 'R' line (Restorer line)

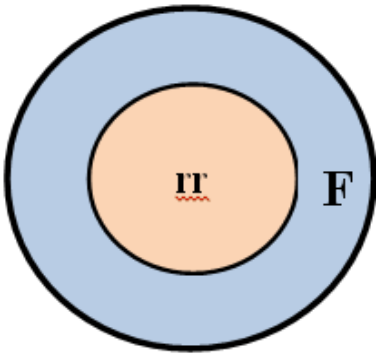

Fig. 3: 'B' line (Maintainer line)

PTGMS (Photo-Thermo Sensitive Genic Male Sterility)

Li *et al.* (2006) identified it which is induced by short day length (<13 h) instead of long day length. This line is controlled by the interaction of photoperiod and temperature. PTGMS is just similar to the TGMS system in all respects except for the temperature regime in between the Critical sterility point (CSP) and Critical fertility point (CFP), where the photoperiod sensitivity is observed. Fertility was restored when day length was >13.5 h (reverse of PGMS). This reversal is attained within temperature range of 23-28°C and is known as short day male sterility (SDMS).

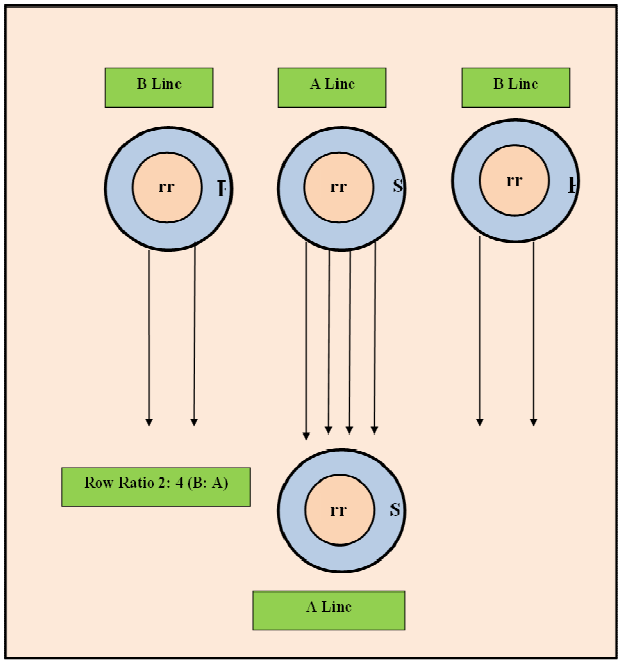

Fig. 4: Maintenance of 'A' line

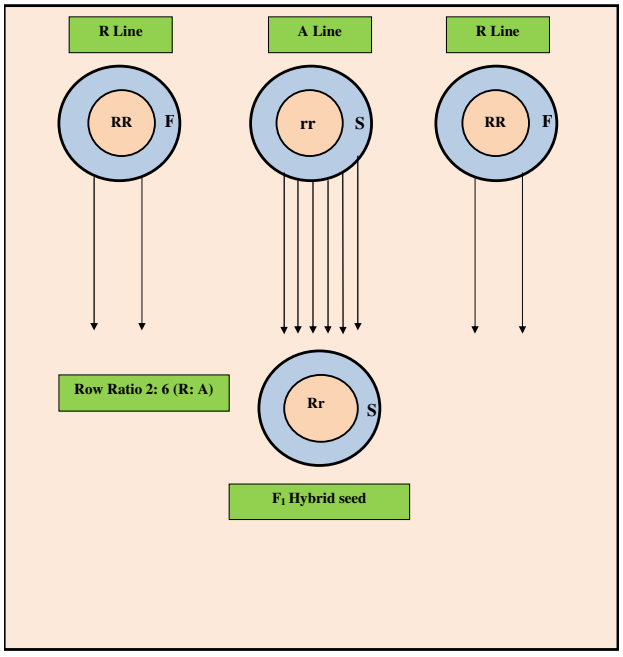

Fig. 5: Hybrid seed production by utilizing R and A lines

Hybrid Seed Production through EGMS System

This system could not become practically feasible in India as well as in other countries till date. This needs a specific environment for multiplication of EGMS lines and separate environment for production of hybrid seed where EGMS gene(s) are able to express. However, this system has become practically feasible in China where it is being used at commercial scale. Since EGMS system has many advantages over other systems, it is necessary to explore possibilities for its practical feasibilities in other countries also. India is working hard in this direction. Table 4 gives a list of important EGMS lines identified.

Apomixis

In case of apomixis, the F_1 plants will produce seeds without fertilization which will be true to the type of parent. In such case, the heterozygosity will be fixed. Hence, the hybrid seed production will be as easier as of normal seed production of inbred varieties. But till date, this technique could not be developed in rice. Efforts in identifying apomixis in rice and its wild accessions did not provide promising results. Induction of apomixis has been reported in rice through use of physical and chemical mutagens (Chen, 1992).

Chemically Induced Male Sterility (CIMS)

In India, this system is not being used at commercial scale due to environmental concerns. This non-genetic method of inducing male sterility involves the use of chemicals called hybridizing agents (CHA's) or Gametocides. These chemicals kill the male gametes and make the plant male sterile. This method is very useful for plants with bisexual flowers in which it is difficult to obtain GMS or CGMS. Chemicals which have been evaluated in rice are, arsenics, GA_3, ethrel, FW450, MH etc. (Table 5). Out of these, only zinc methyl arsenate and sodium methyl arsenate have been reported to be effective for producing commercial hybrids in China (Zhao *et al.,* 1988). Hybrids produced by chemically induced male sterility are also called two-line hybrids in rice. Chemically induced male sterility is used sporadically because the effective and safe chemicals for inducing male sterility are not available.

Advantages and Disadvantages of Hybrid Rice Technology

Advantages

1. Average yield of rice hybrids is 15-35% higher when compared to the high yielding varieties of that group.
2. Increased vigour which makes them more competitive with weeds.
3. Quantity of seed used in hybrid rice is significantly less than the seed used in conventional high yielding varieties.
4. Average productivity and total return to total input cost is significantly higher in hybrid rice than in conventional high yielding varieties.
5. The nursery area required is lesser as compared to conventional high yielding varieties.
6. Hybrids are short duration in nature with resistance/tolerance to major biotic and abiotic stresses.
7. Hybrid seed production generates more employment.

Table 4: Some Important EGMS lines identified

Environment Sensitive Genic Male Sterility (EGMS) lines	
Photoperiod sensitive GMS	Temperature sensitive GMS
Nongken 58 S (China)	Annong 810 S (China)
EGMS (USA)	Hennong S (China)
201 (USA)	5460 S (China)
CIS 28 – 10 S (China)	ATG-1 (India)
Zhenong S (China)	Norin PL 12 (Japan)
X 88 (Japan)	IR 32364 (IRRI)
*Pei-Ai*64S (China)	IR 68945 (IRRI)
7001 S (China)	IR 68949 (IRRI)

Source: Rice Knowledge Management Portal, DRR, Hyderabad, India

Table 5: List of chemicals, concentration and growth stages for application

Chemical	Concentration	Growth stage for application
Ethrel	800-1000 ppm	Prior to anthesis
Monosodium methyl or Arsenate (MGI)	0.02 % or 2000 ppm	Uni-nucleate pollen stage
Sodium methyl arsenate	0.02 % or 2000 ppm	Five days before heading

Source: Rice Knowledge Management Portal, DRR, Hyderabad, India

Table 6: CMS type, source and method

CMS type	Source	Method
Guang Nong 1	*O. sativa*	Irradiation
CMS-FA	*O. rufipogon*	Wide hybridization
Dong B 11A	*O. rufipogon*	Wide hybridization
D62wxA	*O. sativa*	Irradiation
FueA6	*O. sativa*	Irradiation
Vytilla-3	*O. sativa*	Spontaneous mutation
IR66707A	*O. perennis*	Wide hybridization
IR69700A	*O. glumaepetata*	Wide hybridization

Source: Rice Knowledge Management Portal, DRR, Hyderabad, India

Disadvantages

1. Farmers may not use their own seed from one year to next year hence they have to purchase fresh seed every year.
2. Seed cost is almost 2.5 times higher for hybrids than of conventional high yielding varieties.
3. Hybrid rice seed production technology is both labour and knowledge intensive.
4. Majority of the hybrids developed till date are lacking in quality traits.
5. Unpredictable environmental condition may affect sterility expression during seed production resulting to seed purity problems.
6. Hybrids require more doses of fertilizers for higher gain.

Future Strategies to Make Hybrid Rice Technology more Popular and Economical

Enhancing the hybrid rice seed productivity to reduce the seed cost: a) Enhancing row ratio in three line system by proper technique of higher pollen dispersal. In India, a ratio of 2: 8 or 2: 10 (R: A) is followed. Seed production has been improved in China by increasing the ratio up to 2:16, which should be made possible in other countries too. The hybrid seed productivity should be enhanced atleast up to 2.5-3.0 tonnes ha^{-1} to make the availability of hybrid seed at cheaper rate.

b) Adoption of two line system: It does not require maintainer line, which reduce the labour, expenditure and area requirement. Magnitude of heterosis in two line hybrid is also 5-10% higher than in three line hybrids as it does not have cytoplasmic penalty.

Enhancing heterosis: a) We have to enhance the magnitude of heterosis in rice to make it more economical and income generating.

b) Rao and Kulkarni (2004) found heterobeltiosis for grain yield in inter-subspecific (I/J) hybrids 25.2% and standard heterosis 56.8%, whereas in intra-subspecific (I/I) hybrids 9.3% heterobeltiosis and 19.5% standard heterosis.

c) Vaithiyalingan and Nadarajan (2010) studied 42 inter and intra subspecific hybrids utilizing seven wide compatible varieties (WCVs) including two *indica* and five tropical *japonica* for nine biometrical characters including grain yield. For most of the characters, the mean heterosis per cent were in the order of *indica/japonica* F_1 >Tropical *japonica/indica* F_1 > *indica/indica* F_1 > Tropical *japonica/japonica* F_1.

Breeding for Parental Diversification (A and R lines)

Single CMS line may create great threat in future; hence we should be ready to diversify the CMS sources. In India, all the hybrids developed till date is based on 'WA' CMS source. In Maize, Texas cytoplasm (CMS-T) became susceptible to Southern leaf blight epidemic caused by *Drechslera maydis* during 1970 in USA then other sources CMS-C and CMS-S began to be used for hybrid seed production. Rice hybrids also pose the risk of same vulnerability to disease and pests due to narrow genetic background of CMS sources. Considering this, search for new CMS sources and their integration in hybrid rice breeding is a major thrust in three line hybrid rice breeding strategy. Some new sources have been developed for diversification of male sterile cytoplasm in rice (Table 6). However, none of them have been found stable and effective as 'WA' cytoplasm. The D-type CMS has been used in China to develop a few popular hybrid rice varieties.

Breeding Super Hybrid Rice

At present super hybrid rice combinations developed in China have low seed setting rate, poor yield stability and weak adaptability, caused by their genetic disharmonies. Incorporation of the characteristics of high photosynthetic rate from other species into rice plants is of importance for future super hybrid rice breeding.

Table 7: List of identified genes and linked marker

S. No.	Gene	Linked Marker	Recurrent Parent	Donor parent	End product	References
Bacterial blight (BB)						
1.	Xa 21	pta248:Xa21	Minguhi63 (Restorer line)	IRBB21	BB resistance Improved hybrid developed	Chen *et al.*,2000
2.	xa13 and Xa 21	RG136:xa13 pta248:Xa21	Pusa Basmati-1	IRBB55	Developed Improved Pusa Basmati-1(Pusa 1460)	Joseph *et al.*,2004 Gopala Krishnan *et al.,* 2008
3.	Xa7 and Xa21	M1,M2,M3, M4 and M5:Xa7 pta248:Xa21	Minguhi63	Minguhi63 (Xa7) and Minguhi63 (Xa21)	Improved version of Minguhi63 (Xa7) and Minguhi63 (Xa21) developed	Zhang *et al.,* 2006
4.	xa5,xa13 and Xa21	RG556:xa5 RG136:xa13 pta248:Xa21	Sambha Mahsuri	SS1113	Developed BB resistance Improved Sambha Mahsuri	Sundaram *et al.,* 2008
5.	xa13 and Xa 21	RG136:xa13 pta248:Xa21	Pusa 6B and PRR78 (Parental line of PRH10)	Pusa 1460	Developed BB resistance Pusa1601 and Pusa1605	Basavaraj *et al.,* 2010
6.	xa5, xa13 and Xa21	RG556:xa5 RG136:xa13 pta248:Xa21	BPT5204	IRBB55 IRBB13 IRBB21 IRBB59	Developed BPT5204 with 3 gene combination	Kottapalli *et al*., 2010
Bacterial blight + Restorer gene						
7.	Xa21,Rf3 and Rf4	pTA248:Xa21 RM10313:Rf3 RM25654:Rf4	KMR-3R	S1113	Developed BB resistance KRH2	Hari *et al*., 2011
Blast						
8.	Piz5 and Pi54	AP5930:Piz5 RM206:Pi54	PRR78	C101A51 Tetep	Developed Blast resistance PRR78	Singh *et al*., 2012
Brown Plant Hopper (BPH)						
9.	Bph1 and Bph2	em24G:Bph1 KPM2:Bph2	Tsukushibare	PL4:Bph1 IR1154243:Bph2	BPH Resistance pyramided ABL developed	Sharma *et al*., 2004
10.	Bph25 Bph26	S00310:Bph25 RM5479:Bph26	Taichung 65	ADR52	Developed lines carrying Bph25 and Bph26	Myint *et al*., 2012
Gall Midge						
11.	Gm-2 Gm-6(t)	XRG476: Gm-2 Gm-6(t)	Duokang Phalguna	Duokang (Gm2) Phalguna (Gm6t)	Developed lines with both genes	Katiyar *et al*., 2001

Breeding for Transfer of Resistance for Biotic Stress in A and R Lines through Marker Assisted Selection

Marker assisted selection (MAS) refers to indirect selection for a desired plant phenotype based on the banding pattern of linked molecular (DNA) markers. Marker-assisted backcrossing is the simplest form of MAS, in which the goal is to incorporate a major gene from an agronomically inferior source (the donor parent) into an elite cultivar or breeding line (the recurrent parent). The desired outcome is a line containing only the major gene from the donor parent, with the recurrent parent genotype present everywhere else in the genome. Now this technique is being utilized to transfer the resistance genes for biotic stress into A and R lines to improve their overall genetic constitution which will ultimately improve the constitution of hybrid seeds produced thus making them more resistance towards stresses (Table 7).

Screening of Large Number of Restorer Lines through Marker Assisted Selection/Conventional Breeding

Molecular markers for R genes are now available to screen the full restorer lines hence, it is helping the breeders to screen all the genotypes in a lesser time as restorers and maintainers will ultimately help to develop new CMS lines as well as new genotypes. Restoration of WA-CMS in rice is controlled by two nuclear gene *Rf3* and *Rf4*. The SSR marker RM1 is linked with *Rf3* gene on the short arm of 1st chromosome (Ahmadikhah *et al.,* 2007) and Microsatellite markers RM443 and RM315 were flanking *Rf3* gene at a genetic distance of 4.4 and 20.7 cM on chromosome 1 respectively (Shah *et al.,* 2012). The gene *Rf4* was flanking by two SSR markers RM171 and RM6737 on the long arm of 10th chromosome at distance of 3.2 and 1.6cM, respectively (Shah *et al.,* 2012). Sheeba *et al.* (2009) reported that *Rf4*, a major fertility restoration locus on Chromosome 10 was constructed and SSR marker RM6100 was observed to be very close to the gene at a distance of 1.2 cM. The accuracy of the marker RM6100 in predicting fertility restoration was validated in 21 restorers and 18 maintainers. Revathi *et al*. (2013) reported that the SSR marker RM6100 linked to *Rf4* gene on chromosome 10 and RM10313 linked to Rf3 gene on chromosome 1 showed eighty five and eighty one percentages, respectively. Though, conventional breeding takes more time and space to identify large number of genotypes even then it is still being used to identify the fertility restorer lines to be used for developing new hybrids in rice (Sharma *et al.*, 2012).

Breeding for Different Agro-climatic Zones and Agro-ecosystem

The available hybrids are popular in the irrigated upland to medium lands. However, there is need to develop hybrids suited to rain fed lowlands as well for other situations also.

Hybrids for Longer Duration (140-150 Days) to Replace Longer Duration Mega Varieties like, MTU 7029 and BPT 5204 in India

Majority of the rice hybrids developed in India are generally of short duration which may not be compared for yield potential with the mega varieties of longer duration. Hence, there is an urgent need to develop longer duration hybrids in rice.

Hybrid for Quality Traits

Majority of the hybrids developed in India are lacking in good quality which is a major problem in large scale spread of hybrid rice in the country. Majority of the Indians prefer non-sticky cooked rice whereas most of the early hybrids are showing stickiness. Farmers get higher price of long slender aromatic varieties which is lacking in most of the hybrids developed in India. If hybrids with these quality traits are developed, it will certainly help the country in large scale adoption of hybrid rice technology. However, India has become the first country in releasing Basmati type of hybrid (PRH-10) in 2001 which became very popular in the country.

Conclusion

Rice is one of the most important staple foods. Hybrid rice exploits the phenomenon of heterosis which increases yield about 15-25% over HYVs. In case of rapidly increasing population and decreasing natural resources, hybrid rice is one of the most important and practically feasible technologies to achieve the targeted food grain production. Fast advances in molecular biology and biotechnology offer new hopes to design hybrid rice plants with higher yielding potential, better nutritional quality, resistance to biotic and abiotic stresses with higher nutrient and water use efficiency.Three types of male sterility (CGMS, EGMS, CHA's induced) have been used in hybrid rice seed production. India is using CGMS system (3 line system) for hybrid rice seed production. Improvement in hybrid rice seed production technology will further reduce the cost of hybrid rice seed. Hybrid rice seed production technology is both labour and knowledge intensive. This will also generate more and more employment. The available hybrids are popular in the irrigated upland to medium lands. However, there is need to develop hybrids suited to rainfed lowlands as well as of longer duration to replace longer duration mega inbred varieties. Hybrids for meeting specific cooking qualities should also be developed to enhance the hybrid rice area in the country.

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