HYBRID RICE SEED PRODUCTION TECHNOLOGY AND ITS IMPACT ON SEED INDUSTRIES AND RURAL EMPLOYMENT OPPORTUNITIES IN ASIA

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ABSTRACT

The successful commercialization of hybrid rice in many parts of the word is linked to the development of hybrid seed production technology. Although rice is a self-pollinated crop, a hybrid seed production mechanism has been developed using systems based on cytoplasmic and environmentally sensitive genetic male sterility. Chinese seed growers obtain on average 2.5 mt/ha seed yields (range 1.5 to 7.4 mt/ha). Outside China, in tropical countries, mean seed yields are about 1.2 mt/ha (range 0.5 to 4.0 mt/ha). Hybrid seed production technology is economically viable in China and other countries with abundant and cheap labor, because it requires about 50 mandays/ha more labor than normal rice cultivation.

INTRODUCTION

Commercial exploitation of hybrid vigor is one of the most important applications of genetics in agriculture. It has not only contributed to food security, but has also benefited the environment (Duvick 1999). It is the basis of a billion-dollar agribusiness which has generated significant employment opportunities all over the world. Among the various crop species in which hybrid varieties are used commercially, rice ranks very high. Rice hybrids were first commercialized in the late 1970s in China. During the past decade, Vietnam, India, the Philippines, Bangladesh and the United States have also begun the commercial production of hybrid rice.

About 15 million ha (50%) of rice in China are hybrid varieties, producing 103.5 million mt of paddy annually (an average yield of 6.9 mt/ha). The remaining 50%, planted in inbred high-yielding varieties, produces 81 million mt (5.4 mt/ha). Thus, on average hybrid rices in China yield about 27% (1.5 mt/ha) more than the inbred high-yielding varieties.

The commercialization of hybrid rice technology in tropical countries has been facilitated by the research initiated in 1979 at the International Rice Research Institute (IRRI). It was soon recognized that Chinese rice hybrids were not suited to the tropics, and their grain quality was poor compared to the popular inbred high-yielding varieties grown in tropical countries. Therefore, IRRI researchers concentrated on developing suitable parental lines specially for the tropics, using the CMS system which had been found to be effective in China.

Within a decade, some commercially usable CMS and restorer lines and some elite hybrids were identified and shared with NARS for evaluation and utilization. Some of these hybrids were released for commercial cultivation in the Philippines (IR64616H, IR68284H), India (IR64611H, IR64618H, IR69690H), Vietnam (IR64615H, IR64616H, IR69690H) in the years 1993-1998. Some IRRI CMS lines, IR58025A and IR62829A, were also used by national programs to develop local hybrids in India (e.g. APHR-1, APHR-2, CORH 2, KRH 2, ADTRH 1, etc)

Keywords: CMS, cyatoplasmic, GMS, hybrid rice, male sterility, rice, parental lines, PGMS, photosensitive genic, thermo-sensitive genic.

and the Philippines. Concurrently, several private seed companies in Asia were also provided with IRRI-bred parental lines.

Currently, about 610,000 ha are covered with hybrid rices in Vietnam (340,000 ha), India (200,000 ha), Bangladesh (50,000 ha), USA (10,000 ha), Philippines (5,000 ha) and Myanmar (5,000 ha). These have given on average about 20-25% (1 - 1.5/ha) higher yields than the inbred HYVs, thereby contributing towards higher on-farm productivity. Currently, hybrid rice technology is considered a viable option to increase rice yields globally (Yuan 1994, Virmani 1994, Janaiah and Hossain 2000).

Since rice is a self-pollinated crop, hybrid seed production must be based on male sterility systems. These may be cytoplasmic (CMS), thermo-sensitive genic (TGMS) or photo-sensitive genic (PGMS). Most of the commercial hybrids used in China and elsewhere are based on a CMS system, although TGMS and PGMS systems are also becoming used commercially (Yuan, pers. comm.). Hybrid seed production technology involving these male sterility systems is complex and labor-intensive. It also requires a sophisticated seed industry infrastructure.

This Bulletin describes the technology for hybrid rice seed production, its economic viability and impact on farmers and the seed industry, and its rural employment opportunities. Opportunities for vegetative propagation in hybrid rice cultivation are also discussed.

THE TECHNOLOGY

Hybrid rice seed production technology is different from that for inbred rice seed production, and is more complex than the seed production for many other hybrid crops. Currently, the most popular male sterility system is the CMS (popularly known in China as the three-line system). This utilizes three different lines, namely a cytoplasmic male sterile line (A line), a maintainer (B line), and a restorer (R line). Using this system for the commercial production of hybrid seeds involves two major steps. The multiplication of the A line (female parent) must be carried out before the production of hybrid (F_1) seed.

The other system, which is gaining popularity in China and Vietnam, involves a seed parent which is an environmentally sensitive genetic male sterile (EGMS) or S line. This system requires neither a maintainer (B) nor a restorer (R) line. The seed parent can be multiplied just like any conventional inbred when planted in a fertility-inducing environment. When planted in a sterility-inducing environment, it becomes male sterile and may serve as a seed parent in producing F_1 seed of a hybrid. Any line found to form heterotic combinations with a particular S-line can be used as its pollen parent to produce a hybrid. Since this system involve two lines (TGMS or PGMS, and a pollen parent) to produce the hybrid seed, this system is also known as a two-line system. The three- and two-line systems for hybrid rice seed production are shown in Fig. 1.

HYBRID SEED PRODUCTION MECHANISM IN RICE

For hybrid rice seed production to succeed, a sufficient number of pollen grains must be deposited on the stigma lobes of each spikelet of the seed (male sterile) parent. It helps if the pollen parent grows to a greater height than the seed parent. Other plant characteristics which influence this include small and horizontal flag leaves, the number of panicles per square meter, the number of spikelets per panicle, good panicle exsertion, and synchronized flowering of seed and pollen parents. The floral traits influencing outcrossing in rice include: stigma size, style length, stigma exsertion (in seed parent) and anther length, filament length, and pollen number/anther (in pollen parent). The flowering behavior traits influencing outcrossing in rice are: number of days of blooming, time of blooming, duration of blooming, duration of floret opening, and angle of floret opening. The environmental factors influencing outcrossing in rice include temperature, relative humidity, light intensity and wind velocity. The relationship of all these characteristics is discussed at length by Virmani (1996). In China, conditions favorable for good outcrossing in rice have been identified as: a daily temperature of 24-28°C, a relative humidity of 70-80%, a diuranal difference in temperature 8-10°C and sunny days with a breeze (Xu and Li 1988). Suitable field conditions include: fertile soil, a

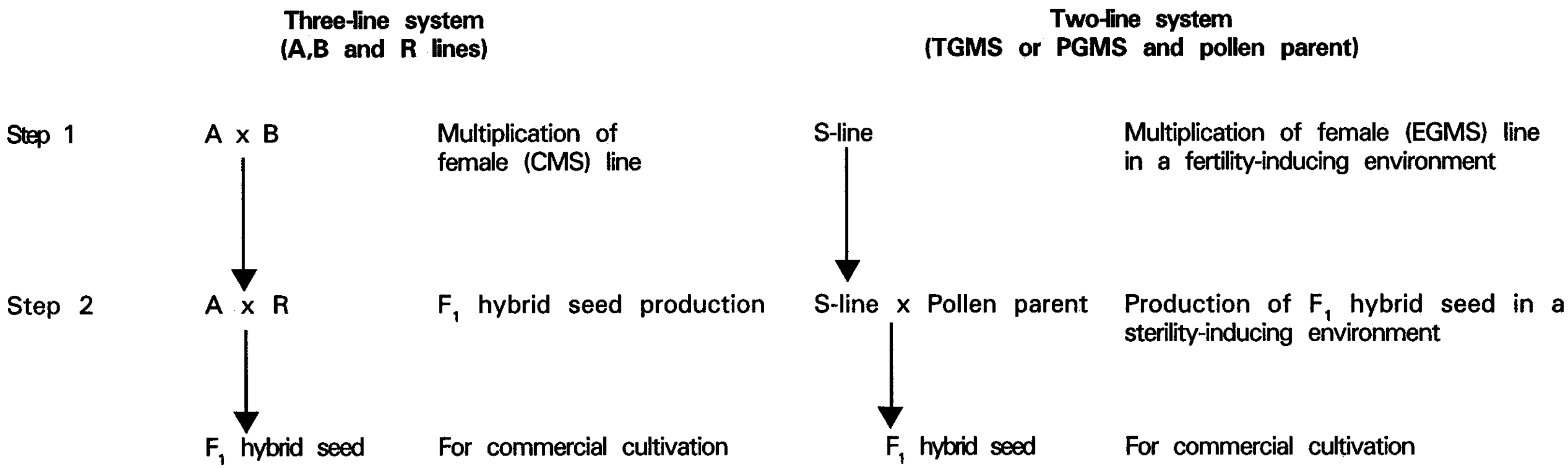

Fig. 1. The three- and two-line systems for hybrid rice seed production

dependable irrigation and drainage system and a low risk of disease and insect infestations.

GUIDELINES FOR HYBRID RICE SEED PRODUCTION

Seed yield from a male sterile line used in hybrid rice seed production is a function of three factors. First is the yielding ability of the male sterile line, as determined by the yielding ability of its maintainer, the fertile counterpart. Second is the proportion of the male sterile line to the pollen parent. The third is the outcrossing rate of the male sterile line. Improvement in any of these three factors can help to increase the seed yields of hybrid rice.

Extensive research has led to the identification of the following guidelines for successful hybrid rice seed production (Yuan 1985, Mao 1988, Virmani 1994a).

1. Selection of seed and pollen parents with synchronized time of anthesis.
2. Selection of seed parents with long, exserted stigma, longer duration, and wider angle of floret opening.
3. Selection of a pollen parent with a high percentage of residual pollen per anther after anther exsertion. High pollen shedding potential is attained by getting 2000 - 3000 spikelets/m^2 to bloom per hour during peak flowering period.
4. Synchronization of flowering time of the two parents by seeding them at different dates depending on their growth duration or estimated accumulated temperature requirements for initiatiion of flowering.
5. Use of optimum seed parent:pollen parent row ratio such that the ratio of spikelet number per unit area of seed parent and pollen parent is about 3.5:1.
6. Use of seed and pollen parents with small and horizontal flag leaves, or cutting long and erect flag leaves.
7. Use of gibberellic acid (GA_3) to improve panicle exsertion and prolong duration of floret opening and stigma receptivity.
8. Planting of seed parent pollen parent rows across the prevailing wind direction and use of supplementary pollination with a rope or stick when wind velocity is below 2.5 m/sec.
9. Selection of optimum time of flowering of parential lines in seed production plots.

PRACTICES FOR HYBRID RICE SEED PRODUCTION

Practices involved in producing hybrid rice seeds using a male sterility system include the following (Yuan 1985, Virmani and Sharma 1993, Virmani 1994a).

Use an isolated field

A field should be used which is isolated from other rice varieties by distance (50-100 m), time of flowering (at least 3 weeks) or some natural or artificial barrier. The isolation distance can be decreased by increasing the number of pollen parent rows around the seed production plot. Barrier isolation can be effected through topographical features, or by the use of tall plants or artificial obstacles to block pollen movement.

Timing of seeding of parent lines

The two parental lines should be sown and transplanted at the right times so that their flowering is synchronized. This is the most critical step in hybrid seed production, and is practiced by using one of the three methods described below:

- The seeding date of the two parents can be determined according to the difference in the time they take to reach maturity. The parent which matures earlier must be sown later than the other parent.
- The seeding date of the two parents can be determined by the difference in the number of leaves at the main culm. If this trait is stable, the date of seeding of the early heading parent can be decided according to the predetermined number of leaves present on the later heading parent.
- The differential seeding of parental lines can be based on their effective accumulated temperature (EAT) from seeding to flowering. The EAT of a particular variety is calculated by summing up the mean temperature of days with a range within 12°C to 27°C. The parent which has a higher EAT is sown earlier, and the other parent is sown after the difference in EAT between the two has accumulated.

Optimum ratio of seed parent:pollen parent plants

The optimum seed parent:pollen parent ratio must be used, according to the spikelet number per panicle of parental lines, and the size of the pollen load of the pollen parent. The seed parent is planted densely, to increase the number of spikelets per square meter. The pollen parent is more widely spaced, to promote tillering and help ensure that the pollen load is greater over a longer period.

The optimum ratio for plants of the seed: pollen parent should ensure 3.5 spikelets of the seed parent for each spikelet of the pollen parent. Some commonly used seed parent:pollen parent ratios are 10:3, 6:2 and 14:2. In extreme cases, a ratio of 16:2 has been used. In the United States, a ratio of 18:6 is used for mechanized hybrid seed production.

Good cultural management

The seed production plot must be given good cultural management. Weeds, diseases and insects must be controlled, and the optimum fertilizer rate must be applied. If the panicle initiation stage of the two parental lines is found to occur at different times, they should be given different application rates of nitrogen, phosphate and potassium fertilizer, to adjust the flowering date of the parental lines by 2-5 days.

If the parental lines have long, erect flag leaves which might obstruct the movement of pollen, the flag leaves should be clipped by one-half or two-thirds of their length, one to two days before the initial heading. However, this practice has the negative effect that it may spread diseases such as bacterial blight, and sheath blight through the wounds inflicted on the leaves. Besides, this practice also reduces photosynthetic activity. Parental lines possessing short narrow, flag leaves do not need to be clipped.

GA_3 should be sprayed on parental lines which show poor panicle exsertion. Besides improving panicle exsertion, GA_3 also increases the stigma exsertion rate, as well as the time during which the spikelet is open and the stigma is receptive. Differential application of GA_3 also increases the relative height of the pollen parent over the seed parent. GA_3 is generally sprayed using a knapsack sprayer. Spraying begins when 5-10% of the rice plants are at the heading stage, and lasts for 2-4 consecutive days.

Spraying should be done on a calm sunny day, usually in the afternoon. It should not be carried out if rain is expected within 24 hours.

Hybrid rice seed producers in China use a very high dosage (150-300 gm/ha) to get high seed yields. However, outside China the high cost of GA_3 limits seed growers to using only 45-50 gm/ha. The use of an Ultra Low Volume (ULV) sprayer has been found to reduce GA_3 dosage to 15-20 gm/ha, and give seed yields similar to those from spraying 45-50 gm GA_3 from a knapsack sprayer.

The horizontal dispersal of pollen grains can be increased by shaking the panicles of the pollen parent by pulling a rope between two people, or stirring the canopy layer of the pollen parent with a bamboo stick (supplementary pollination). This should be done during the anthesis of the pollen parent. Either method may increase outcrossing, and hence seed yields. Care should be taken that panicles are not broken at the neck.

Roguing of off-types should be carried out at maximum tillering, flowering and maturity stages, to prevent any cross-pollination between them and the true-to-type seed and pollen parent plants.

Pollen and seed parents should be harvested, threshed, dried and cleaned separately and carefully, to avoid any mechanical mixture of seed of parental lines.

Using the above practices, seed yields of 0.5 to 4 mt/ha (mean 1.3 mt/ha) have been obtained in the tropics. However, because of the vast experience of China's seed growers and specialized hybrid rice seed production, yields in China range from 1.5 mt/ha to 7.4 mt/ha (mean 2.5 mt/ha). In the late 1970s, average hybrid rice seed yield in Mainland China were 0.67 mt/ha. Currently, these have increased to 2.5 mt/ha. This increase in seed yield is a associated with the modified practices shown in Table 1.

QUALITY CONTROL FOR HYBRID RICE SEED

Quality control is vital to the widespread adoption of hybrid rice. Farmers who buy

Table 1. Progressive modification of techniques of hybrid rice production in China during the late 1970 to late 1990s to increase seed yields.

Technique	Period		
	Late 1970s	Late 1980s	Late 1990s
Row ratio	1-2:6-8	2:10-12	2:14-18
Width of a female parent strip (m)	1.5	2.0	2.5
Plants/hill			
A line	1	2	2
R line	1	1	3-4
Transplanting density (cm)			
A line	16.5 x 16.5	15 x 15	13 x 13
R line	20 x 20	20 x 20	17 x 30
Hills/ha (x 1000)			
A line	320	450	590
R line	67	50	27
Plants/ha (x 1000)			
A line	320	900	1060
R line	67	50	100
Plants/ha (x 1000)	2100	2600	3200
Dosage of GA_3 (g/ha)	0-45	75-120	180-220
Concentration (ppm)	20-40	40-60	100
Seed set percentage	10-15	25-30	45-50
Clipping of flag leaves	Yes	Yes or no	No or lightly
Yield (mt/ha)	0.54	1.80	2.50

Table 2. Seed standards for parental lines and F1s of hybrid rice in China (Mao 2001)

	Seed grade	Purity (>%)	Cleanness (>%)	Germination (>%)	Moisture (>%)	Weed seeds (> grains/kg)
A line	Nuclear seed	100.0	99.8	98.0	13.0	0
	Foundation seed	99.9	99.0	96.0	13.0	0
	1st class seed	99.5	99.0	96.0	13.0	0
	2nd class seed	99.0	97.0	95.0	13.0	5
B line	Nuclear seed	100.0	99.8	98.0	13.0	0
	Foundation seed	99.9	99.0	96.0	13.0	0
	1st class seed	99.5	99.0	96.0	13.0	0
	2nd class seed	99.0	97.0	93.0	13.0	5
R line	Nuclear seed	100.0	99.8	98.0	13.0	0
	Foundation seed	99.8	99.0	96.0	13.0	0
	1st class seed	99.5	99.0	96.0	13.0	0
	2nd class seed	99.0	97.0	93.0	13.0	5
F_1 hybrid	1st class seed	98.0	98.0	93.0	13.0	0
	2nd class seed	96.0	97.0	90.0	13.0	5

Note: 1. The 1st and 2nd class seeds are certified seeds.
2. The sterility and sterile plants of nuclear and foundation seeds of A line both should be 100%.
3. The restoring rate of nuclear and foundation seeds of R line both should be higher than 85%.

expensive hybrid seeds expect high quality. Quality control is carried out throughout the whole process of seed production. It includes the nucleus, breeder, foundation and certified seed production of both parental lines and F_1 hybrids.

Seed quality standards are met by intensive roguing of off-types (from seeding to harvesting) and careful handling during harvesting, threshing, drying, cleaning, processing, bagging and labeling. Grow-out tests, germination tests, seed vigor tests etc. should also be done before the seeds are sold commercially. China has a well-established hybrid rice seed industry and national standards for hybrid rice. Seed quality standards are in place (Table 2) and being followed. In other countries where hybrid seed production is more recent, standards vary and are still to be formalized.

VEGETATIVE PROPAGATION OF HYBRID RICE

Vegetative propagation of rice is well-known. Adult plants can be raised from seedlings, tillers, culm cuttings or by ratooning. Clonal propagation of rice was proposed in early sixties to exploit hybrid vigor in rice (Richharia 1962). However, no serious attempt was made to develop this as a technology. Since the commercialization of hybrid rice technology in China in 1976, agronomists and farmers have tried using vegetative propagation in various ways to reduce the seed rate, and hence the seed cost, of commercial rice hybrids. These approaches include double transplanting and ratooning.

In double transplanting, hybrid seeds are sown densely in the seed bed. When the seedlings reach the 2-3 leaf stage, they are transplanted into a field nursery, using a wide spacing of 33 x 10 cm to induce more tillering. After 25-30 days, tillers are separated and transplanted into the main rice field. Although double transplanting can reduce the seed rate of hybrid rice significantly, it does increase the labor cost.

In subsistence farming, where family labor is readily available and there is no other opportunity cost, this method may be useful. However, in situations where labor is either not available or can earn more elsewhere, this approach may not be economical.

Ratooning of hybrid rice has been tried with varying degrees of success. Recently, successful vegetative propagatioin of rice has been achieved by splitting and transplanting the ratoon seedlings of an F_1 rice hybrid in Bangladesh (M.A. Mazid, pers. comm..). This approach would be practical with resource poor farmers who can use family labor but who cannot afford the full cost of hybrid seed.

ECONOMIC VIABILITY OF THE PRODUCTION OF HYBRID RICE SEED

The availability of quality seed at a reasonable price is a crucial factor behind the large-scale adoption of hybrid technology for any crop. This has been demonstrated by the success of hybrid varieties of maize, pearl millet, sorghum, sunflower and cotton, all of which are supported by economical and efficient seed production and distribution systems in the countries where the hybrids are commercialized. Chinese success in the large-scale adoption of hybrid rice can also be attributed to the efficient and economical hybrid seed production and distribution system, organized by the state-owned seed industry.

Hybrid rice seed production technology is considered labor- and knowledge-intensive. It involves various risks, especially in the early stages when seed producers are still lacking in experience. Typical problems are poor synchronization of the parental lines, and unfavorable weather. At present, commercial production of hybrid rice seed outside China is limited to India, Vietnam, the United States and the Philippines. Seed growers will engage in hybrid rice seed production only if it is more profitable than inbred varieties, and if the additional profit is enough to compensate for the greater risks and level of skill involved.

India

Studies conducted in the Indian states of Andhra Pradesh, Karnataka and West Bengal showed that on average, labor accounted for about 48% of the total cost of hybrid rice seed (Janaiah and Hossain 2000). Hybrid rice seed production requires about 340 mandays/ha, about 50 mandays/ha more than for ordinary rice cultivation. Hybrid seed production requires additional labor for extra

Table 3. Comparative cost-return profile for hybrid rice seed production and commercial inbred rice production in India (1997-98 crop year)

Costand returns	Hybrid seed production (US$/ha)	Inbred rice production (US$/ha)
Cost		
Seed[a]	70.0	14.0
Fertilizers & manure	123.8	86.8
Gibberellic acid (GA_3)	50.0	-
Labor	315.0	112.5
Plant protection	15.0	13.8
Miscellaneous	71.2	11.9
Total input cost return	645.1	239.0
Yield[b] (kg/ha)	1250	5950
Market price[c] (US/kg)	1.0	0.1173
Return to hybrid seed	1250	-
Return to by-product (male seed and straw)	212.5	41.1
Gross return	1462.5	739.0
Net return	817.4	500.0
Unit cost of production (US$/kg)	0.516	0.040

a: A-line seed in the case of hybrid seed production b: Hybrid seed yield in the case of hybrid seed production
c: Seed price paid to the growers of hybrid seed

Source: Janaiah and Hossain 2000

farm operations such as thin and row planting, supplementary pollination, filling gaps, roguing, GA_3 application, and manual harvesting, threshing and cleaning.

China

In China, the production of hybrid rice seed takes about 375 mandays/ha, 75 mandays/ha more than ordinary rice (He *et al.* 1987).

The cost of female parental line seed (A seed) and gibberellic acid (GA_3) (additional inputs for hybrid seed production) accounted for 9% of the total cost (Table 3). The average cost of producing hybrid seed was US$0.52/kg. The private sector was able to buy hybrid seed from seed growers at US$0.85/kg, while government agencies paid US$1.0-1.1/kg. At an average price of US$1.0/kg, with an average seed yield of 1250 kg/ha, hybrid rice seed production was 65% more profitable than ordinary rice cultivation (Table 3).

Seed companies in India sell hybrid seed produced in India to farmers at US$2.0-2.5/kg. This large margin is needed to keep the private seed companies in business, since the demand for hybrid rice seed is small and the market is dispersed. However, as the technology picks up, economies of scale should reduce the cost of production and increase seed yields. This would allow seed companies to sell hybrid seed at a lower price to farmers. Greater competition in the seed business will also force seed companies to reduce the selling price of hybrid rice. As reported in Table 4, the selling price of hybrid rice seed could be reduced from US$2.50 to 1.0/kg, if seed yields were to increase from their present level of 1.25 mt/ha to 3.0 mt/ha. In such a case, the cost of hybrid seed would fall by US$20-30/ha.

Vietnam

Vietnam, because of its socio-economic and political structure, has been able to develop a strong research-extension-farmer linkage in seed production and distribution, similar to that of China. The top priority for Vietnam's hybrid rice program is to develop an efficient system for the production and distribution of hybrid seed at affordable prices. At present, about 20% of hybrid rice seed requirements are met by seed produced in

Table 4. Effects of increase in seed yield of hybrid rice on cost of seed production and selling price of seed in India, a sensitivity analysis

Scenario	Cost of production (US$/kg)	Selling price (US$/kg)	Seed cost for commercial cultivation @ 20 kg/ha (US$/ha)
I. At current seed yield of 1,250 kg/ha	0.52	2.50	50
II. At seed yield of 2,000 kg/ha	0.32	1.60	32
III. At seed yield of 2,500 kg/ha	0.26	1.30	26
IV. At seed yield of 3,000 kg/ha	0.22	1.00	20

Table 5. Cost-return profile for hybrid rice seed production in Vietnam, 2000, spring

Particulars	Values
Yield of hybrid seed (kg/ha)	2000
Seed price paid to the seed growers (US$/kg)	0.60
Return to hybrid seed growers (US$/ha)	1200
Total cash costs (US$/ha)	800
Net return to hybrid seed growers (US$/ha)	400
Cost of seed production **with** subsidy (US$/kg)	0.40
Cost of seed production **without** subsidy (US$/kg)	0.60

Note: In addition to cash cost (paid-out cost), the Vietnamese government provided a subsidy to the seed growers of US$400/ha.

Vietnam, while the remaining 80% is imported from China. About 600 ha in Vietnam was under hybrid rice seed production in the year 2000, compared to only 173 ha in 1992. Average seed yields increased from about 300 kg/ha to 2500 kg/ha during this period. According to Vietnam's Ministry of Agriculture and Rural Development, hybrid rice seed requirements are about 24,000 mt, if hybrid rice cultivation is to be increased to 800,000 ha by 2005.

The total cost of hybrid rice seed production in Vietnam for the spring crop in 2000 was about US$1200/ha, of which the government provided 30% as a subsidy in the form of free parental line seeds, GA_3, chemical fertilizers, etc. Therefore, the cash cost of seed production paid by the growers was US$800/ha (Table 5). Average seed yields are 2.0 mt/ha, and the current seed procurement price is US$0.60/kg. Thus, the production of hybrid rice seed in Vietnam generates about US$400/ha net profit.

This is 30-35% higher than the profits from ordinary rice. However, the government's subsidy for hybrid rice seed production may not continue forever. If the subsidy is withdrawn, the procurement price of hybrid seed ought to be raised from its present level of US$0.6/kg to 0.8/kg, to compensate. This may lead to an increase of 30% in the selling price, over the current selling price of $1.1-1.2/kg. In order to keep the selling price at the current level without subsidy, the seed yield would have to increase to 3 mt/ha.

The production of hybrid rice seed must be economically viable if it is to attract seed companies. Therefore, seed production can be organized in countries where labor is available at a reasonable price, provided there is a demand for hybrid seed among farmers.

Future demand

Successful development and large-scale dissemination of hybrid rice technology will have a major impact on the seed industry, in view of the fact that rice is a staple food crop in Asian countries. Usually, the private sector does not play much of a role in the early stage of technology development. At this stage, the public sector has to play a leading role.

Once the private sector is convinced that there is a demand for hybrid seed, it is willing to invest in commercial seed production, since hybrid seed production is quite profitable. Public sector research institutions in Asia (IRRI and NARS) have already made great progress in the development of suitable rice hybrids, and have also developed many parental lines that are freely available to the private sector. A number of private seed companies (including 15 in India, six in Bangladesh, three in the Philippines, and one in Vietnam), and a few NGOs and farmers' organizations, have already begun to produce hybrid rice seed.

There is a growing linkage between the public and private sectors, not only in sharing genetic resources, but also in the form of private sector support for public research. Some small seed companies have also started joint ventures with big multinational companies for the production and/or import and marketing of hybrid rice seed in Bangladesh, Vietnam, the Philippines etc..

Some farmers' organizations have also begun hybrid rice seed production, either independently or as a joint venture with a private seed company. These developments may reduce the cost of hybrid rice seeds to as little as US$20-35/ha. This would promote the further adoption of hybrid rice production by small-scale farmers.

IMPACT ON RURAL EMPLOYMENT OPPORTUNITIES

In addition to its profitability, the additional labor cost of hybrid rice seed production is a positive feature in rural Asia. Hybrid rice seed production requires about 50 mandays/ha more labor than normal non-mechanized rice cultivation. It therefore generates additional employment opportunities. This is a great benefit, especially for landless women in countries such as India, Bangladesh, and Vietnam which have a labor surplus.

If hybrid rice technology spreads on a large scale in these countries, it would contribute substantially not only to food security, but also to poverty elimination by generating employment in rural areas. If six million hectares were to be planted in hybrid rice by the year 2010, hybrid rice seed production would generate about 3-4 million mandays of rural employment in Asia.

CONSTRAINTS TO HYBRID SEED PRODUCTION IN ASIA

Hybrid rice seed production is quite complex. Many factors affect the yield and quality of hybrid seed. When China began its commercial production of hybrid seed in the late 1970s, the average yield was less than 0.5 mt/ha. It took many years of experience to achieve its current seed yield of 2.5 mt/ha of F_1 seed production in an area of about 0.14 million ha.

Twenty years after China, several other countries began the commercial hybrid production of hybrid rice seed. In a few small areas, seed yields of 4 mt/ha have been achieved (Ish Kumar, pers. comm.), but average yields still remain low at around 1.2 mt/ha. There are many constraints to the adoption of hybrid rice seed production technology. These are discussed below:

1. Hybrid rice technology in countries outside China was adopted only a few years ago. Seed growers need time to become familiar with the technology, and need more experience of hybrid seed production at specific locations under local climatic conditions.
2. There is a shortage of skilled manpower at the initial stages of seed production technology. Seed production can only be successful if it is supervised by well-trained technicians and carried out by experienced growers.
3. Hybrid rice seed production is highly dependent on use of gibberellic acid (GA^3). Outside China this is quite expensive (more than US$1.00 per gram), because it is imported. In China it is quite cheap (US$0.30 per gram) because it is produced locally, so it does not cost much to apply a high dosage of this growth regulator.
4. The purification of parental lines is vital to the success of any hybrid seed production program. However, it has not received enough attention.

Consequently, parental lines used for hybrid seed production are not pure, which results in poor-quality hybrid seeds.

5. Hybrid rice seed production requires a well-organized seed industry. Apart from China, most countries in Asia have not yet achieved this for hybrid rice seed.
6. Since hybrid rice technology is new in most countries, government policies do not yet motivate and encourage hybrid rice seed production on a large scale.
7. The linkage between public sector research institutes and seed production agencies working on hybrid rice is weak.

FUTURE OUTLOOK

Hybrid rice technology has had a tremendous economic impact in China, where it makes possible the production of about 20 million mt of additional rice each year. This extra production keeps global rice prices in check, so that the urban poor in rice-consuming countries can afford to buy enough rice. Without hybrid rice technology, the world would require 6 million ha more land to produce the same quantity (Duvick 1999). Thus, the technology has contributed not only to food security, but it has also helped indirectly to protect the environment.

The spread of hybrid rice technology would have the same effect in other Asian countries. Since hybrid seed production is labor-intensive, it would also create additional rural employment opportunities in countries with abundant labor.

Hybrid rice seed yields as high as 7.39 mt/ha have been reported from China, and up to 4.8 mt/ha from other countries. Seed yields can be increased by bringing about:

- Further genetic improvement of flowering behavior and floral traits of seed (e.g. exserted stigma) and pollen parents (e.g. abundant pollen);
- Modification of seed production practices; *and*,
- Selection of the most favorable seasons and locations for seed production.

GA_3 application is an important component of hybrid rice seed production technology. Its cost is very high in many countries. High seed yields in China have been achieved with a very high dosage of 150-300 grams per hectare. Outside China, it is essential to reduce the cost of GA_3, either by reducing the dosage or by producing cheap GA_3 locally. Alternatively, a cheaper substitute for GA_3 needs to be found.

The discoloration of hybrid rice seeds caused by tropical fungi is an important problem which needs to be tackled. In China and northwestern India, CMS lines in hybrid rice seed production plots have been found to have a higher incidence of seed-borne diseases (such as paddy bunt, caused by *Neovassia horinda*, and Tak and False Smut caused by *Ustilogonoids virens*) compared to the pollen parents. This can cause a serious outbreak of these diseases in commercial crops of hybrid rice, and therefore needs more attention.

For countries such as Japan, Korea, Malaysia and United States which have a labor scarcity and high wages, hybrid rice seed production needs to be mechanized to make it cost effective. A mechanized hybrid rice seed production system has been developed in the United States (Andrews 2001). Such a system in Asia might use several strategies, such as:

- The use of facultative female sterility (Maruyama and Oono 1983).
- Incorporating a gene for herbicide susceptibility in the pollen parent (Maruyama *et al.* 1991).
- The use of highly heritable differences in grain width (at least 0.7 mm) in seed and pollen parents for mixed planting and mechanized harvesting (Maruyama *et al.* 1991), *and.*
- Incorporation of a phenol reaction (Ph) gene into the pollen parent (Virmani and Maruyama 1991).

For countries lacking suitable seed industry infrastructure, a self-sustaining seed production system (Virmani *et al.* 1993) can be tried, so that farmers can produce hybrid seeds for their own use rather than for sale to others.

Apomixis is the ultimate genetic tool to develop true breeding hybrids and facilitate commercial exploitation of heterosis by even resource poor farmers. (Apomixus is reproduction involving specialized tissue but not dependent apon fertilization: an example is parthenogenis). So far, there is no confirmed report of apomixis in rice. However, research is in progress in Mainland China, at IRRI, and elsewhere, to discover, induce, and/or genetically engineer such rices.

CONCLUSION

Although rice is a self-pollinated crop, significant cross-pollination occurs in male sterile lines. This has made possible the development of economically viable hybrid rice seed production systems in and outside China, yielding 1-3 mt/ha of hybrid rice seeds. More than 30 public and private seed companies outside China are currently involved in developing and/or commercializing hybrid rice technology. These companies are creating additional rural employment opportunities. In the United States, the seed production system has already been mechanized.

For resource-poor rice farmers, the prospect of vegetative propagation of rice hybrids is being explored. Already about 0.61 million ha of paddy land outside China is planted in hybrid rice. This area is likely to increase to about 2 million ha over the next five years. In China, hybrid rice has already contributed significantly towards increased food security and environmental protection, and higher incomes for seed producers. It has also created additional rural employment opportunities. Outside China, the same phenomena are now being seen, and their impact will be felt during the next five to ten years.

REFERENCES

Andrews, R.D. 2001. The commercialization and performance of hybrid rice in the Unted States 2001. In: *Rice Research for Food Security and Poverty Alleviation*, S. Peng and B. Hardy (Eds.). Proceedings of the International Rice Research Conference, 31 March-3, International Rice Research Institute, April, Los Banos, Laguna, Philippines. 692 pp.

Duvick, D.N. 1999. Heterosis: Feeding people and protecting natural resources. In: *Genetics and Exploitation of Heterosis in Crops*. American Society of Agronomy, Inc., Crop Science Society of America, Inc., Soil Science Society of America, Inc.. Madison, Wisconsin, USA.

He, G.I., X. Zhu and J.C. Flinn. 1987. Hybrid seed production in Jiangsu province, China. *Oryza* 24: 285-296.

Janaiah, A. and M. Hossain. 2000. Hybrid rice for food security in the tropics: An evaluation of farm-level experiences in India. Paper presented at the 3rd International Crop Science Congress held in Hamburg, Germany, 17-22 August 2000.

Mao, C.S. 1988. Hybrid rice seed production in China. In: *Seed Health*. International Rice Research Institute, Los Banos, Laguna, Philippines. Pp. 277-282.

Mao, C.X. 2001. Improving seed production to speed up the global commercialization by hybrid rice. 2001. In: *Rice Research for Food Security and Poverty Alleviation*, S. Peng and B. Hardy (Eds.). Proceedings of the International Rice Research Conference, 31 March-3 April 2000. International Rice Research Institute, Los Banos, Laguna, Philippines. 692 pp.

Maruyama, K. and K. Oono. 1983. Induction of mutation in tissue culture and its use for plant breeding. VII. On the female and male sterile rice plants regenerated from seed acalluses. *Jan. Jour. Breed.* 33 (Suppl. 1): 24-25. (In Japanese).

Maruyama, K., H. Kato and H. Araki. 1991. Mechanized production of F_1 seeds in rice by mixed planting. *JARQ* 24: 243-252.

Richharia, R.H. 1962. Clonal propagation as a practical means of exploiting hybrid vigor in rice. *Nature* (London) 194: 598.

Virmani, S.S., J. Manalo and R. Toledo. 1993. A self-sustaining system for hybrid rice seed production. *International Rice Research Newsletter* 18: 4-5.

Virmani, S.S. 1994a. Heterosis and hybrid rice breeding. In: *Monographs on Theoretical and Applied Genetics* 22, S.S. Virmani (Ed.). Springer-Verlag.

Virmani, S.S. 1994b. Prospects of hybrid rice in the tropics and subtropics. In: *Hybrid Rice Technology, New Developments and Future Prospects*, S.S. Virmani (Ed.). International Rice Research Institute, Los Banos, Laguna, Philippines, pp. 7-19.

Virmani, S.S. 1996. Hybrid Rice. *Adv. Agron.* 57: 378-462.

Virmani, S.S. and Maruyama, K. 1991. Some genetic tools for hybrid breeding and seed production in sell pollinated crops.

In: *Proceedings of the Golden Jubilee Symposium on Genetic Research and Education, Current Trends and the Next Fifty Years.* New Delhi (India), pp. 12-15.

Virmani, S.S. and H.L. Sharma. 1993. *Manual for Hybrid Rice Seed Production.* International Rice Research Institute, Los Banos, Laguna, Philippines.

Xu, S.J. and B. Li. 1988. Managing hybrid rice seed production. In: *Hybrid Rice*. International Rice Research Institute, Los Banos, Laguna, Philippines, pp. 157-163.

Yuan, L.P. 1985. *A Concise Course in Hybrid Rice*. Hunan (China): Hunan Science and Technology Press. 168 pp.

Yuan, L.P. 1994. Purification and production of foundation seed of rice PGMS and TGMS lines. *Hybrid Rice* 6: 1-2.