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Rice improvement at IRRI: An example of International Collaboration

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The rice improvement program of International Rice Research Institute (IRRI) is an international and interdisciplinary effort. It has five components, i.e. (1) Germplasm collection, conservation and evaluation, (2) Methodology development, (3) Development of improved germplasm, (4) Exchange and evaluation of germplasm, and (5) Training and staff development. More than 91,000 accessions of cultivated rice and wild species of *Oryza* are being maintained in germplasm bank at IRRI. These are being evaluated for various morphological traits, grain quality and resistance to biotic and abiotic stresses. Methods for accelerated rice improvement have been developed. Superior germplasm has been bred for all the rice growing ecologies with a focus on yield enhancement, shorter growth duration, superior grain quality, resistance to diseases and insects and tolerance to abiotic stresses. More than 600 improved varieties have been selected from the IRRI bred materials and released in rice growing countries of Asia, Africa and Latin America. Rice production more than doubled in a 30-year period and most of the rice growing countries became self-sufficient. The germplasm is shared freely with the national programs on the basis of requests from scientists or through international nurseries. More than 1,000 rice breeders have been trained at IRRI and are leading the rice improvement programs in respective countries.

Key Words: germplasm collection and evaluation, heterosis, male sterility, Rapid General Advance, shuttle breeding, marker-aided selection, anther culture, transformation

Introduction

Rice, *Oryza sativa*, is the world's most important food crop. It is the principal food of more than half of the world's population. Fifty per cent of the calories consumed by world population come from three cereals; rice 23%, wheat 17% and maize 10%. In countries like, Bangladesh, Myanmar, Cambodia and Laos, rice supplies over 70% of the calories. Although rice is grown in about 90 countries spread over 6 continents, more than 92% of rice is produced and consumed in Asia. In 1960s, the average yields of rice in most Asian countries except Japan were between 1.5 and 2.0 t/ha as compared to average yields of over 5 t/ha achieved in temperate-zone countries such as Japan, Australia, Italy and USA. International Rice Research Institute (IRRI) was established in 1960 by the Rockefeller and Ford Foundations at Los Baños, Philippines to apply science to improve stagnant yields on Asian farms. One of the most important research programs of IRRI since its inception has been the rice varietal improvement. It is one of the biggest crop improvement programs in the world. It endeavors to develop and help develop improved germplasm for the diverse rice growing conditions. It is truly an international and interdisciplinary team effort where plant breeders work with scientists in other disciplines such as plant pathologists, entomologists and plant physiologists in developing improved germplasm, which is shared freely with the national rice improvement programs. It has five interrelated components:

- Germplasm collection, conservation and evaluation
- Methodology development
- Development of improved germplasm
- Distribution, exchange and evaluation of germplasm internationally
- Training and staff development

Germplasm collection, conservation and evaluation

Collection, conservation and cataloguing of germplasm is the backbone of any crop improvement program. Since 1962, when the germplasm collection work was initiated, cultivated and primitive varieties and wild species have been collected from most of the rice growing countries. The collections are multiplied at IRRI and various duplicates are removed. An IRRI accession number is assigned to each collection and seed samples of each accession are stored in the germplasm bank. The IRRI collection now includes over 85,997 accessions of *Oryza sativa*, about 1,333 accessions of *O. Glaberrima* and more than 3,696 accessions of wild species of *Oryza* (Jackson, Personal Communication).

The seeds of rice collections are preserved under two storage conditions; (1) approximately 4°C and relative humidity of 35%. Seeds are expected to remain viable for 30–40 years, (2) −10°C and relative humidity of 25%. Seeds are expected to remain viable for 100 years.

IRRI accessions are evaluated for 50 morphological traits, during seed multiplication, for grain quality, for disease and insect resistance and for tolerance to abiotic stresses such as drought, floods, problem soils and adverse temperatures. Each year, numerous seed samples are supplied to rice scientists all over the world on the basis of their requests.

Methology development

IRRI scientists have developed or modified many procedures and methods for the rapid development and evaluation of improved germplasm. IRRI's trainees and visitors are exposed to these procedures. Some of the salient contributions are:

1. Development of screening techniques for evaluation of large number of germplasm entries to identify donor parents for disease and insect resistance and for tolerance to various environmental stresses (Khush 1977).
2. Development of procedures for incorporating multiple disease and insect resistance into improvement germplasm (Khush 1978)
3. Studies on inheritance of resistance to diseases and insects to identify diverse genes for resistance (Khush 1992)
4. Design and modification of a vacuum emasculator for facilitating hybridizaiton work (Herrera and Coffman 1975)
5. Development of procedures for handling large breeding nurseries (Jennings *et al.* 1979)
6. Research on hybrid rice to exploit the phenomenon of heterosis for raising the yield potential (Virmani *et al.* 1981)
7. Use of recurrent selection and population improvement using genetic male sterility to improve quantitatively inherited traits. Recurrent selection is used primarily to promote recombination and to increase the frequencies of favorable genes for quantitatively inherited traits (Chaudhary *et al.* 1981)
8. Use of anther culture to obtain doubled haploid lines from selected crosses (Zapata *et al.* 1983)
9. Single seed descent method of breeding has been modified at IRRI to breed photoperiod sensitive rices. For this purpose, facilities for Rapid Generation Advance to handle the breeding materials were developed as described by Ikehashi and HilleRisLambers (1977)
10. Interspecific hybridication has been employed to transfer useful genes from wild species to cultivated rice (Jena and Khush 1990)
11. For developing improved germplasm for unfavorable environments which do not occur in the Philippines, a shuttle breeding approach was adopted. This involves making crosses between appropriate parents and growing F_1s at IRRI. Planting F_2 populations and alternate generations under target environments in collaborating countries and at IRRI (Khush and Sarkarung 1998)
12. Development of protocols for marker-aided selection (MAS) and its application to rice improvement (Zheng *et al.* 1995)
13. Development of protocols for rice transformation (Datta *et al.* 1997)

Development of superior germplasm

Rice is grown under four major ecologies e.g. irrigated, rainfed lowland, upland and flood-prone (Khush 1984). About 55% of the world rice area is irrigated. Rice growing conditions in this ecology are favorable but disease and insect problems are serious. About 25% of the rice area is classified as rainfed lowland, 12% as upland and 8% as flood-prone (Fig. 1). Rice production

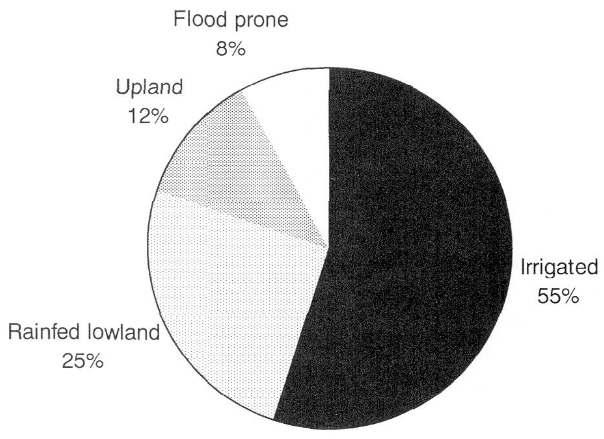

Fig. 1. Distribution of world rice area in different ecologies.

under three latter ecologies is affected by moisture stress or moisture excess (flooding). Thus varietal requirements are quite different for different growing conditions. Therefore, breeding program has been organized with a focus for developing improved germplasm suitable for each of the four ecologies. Improvements in each of the following traits are sought for:

· Yield potential
· Short growth duration
· Superior grain quality
· Multiple disease and insect resistance
· Tolerance to abiotic stresses

Yield potential

Traditional rice varieties had a harvest index (ratio of dry grain weight to total dry matter) of 0.3. To increase the yield potential of rice, it was necessary to improve the harvest index and increase nitrogen responsivement by increasing lodging resistance. This was accomplished by reducing the plant height through incorporation of a gene for short stature, *sd1*, from a Chinese variety called Dee-geo-woo-gen. The first semidwarf variety, IR8, also had combination of other desirable features such as profuse tillering, dark green and erect leaves, and sturdy stems. It responded to nitrogen fertilizer much better than traditional varieties. It had a harvest index of 0.5 and its yield potential was twice that of traditional varieties. Being photoperiod insensitive, it could be planted any time of the year in tropics and subtropics. It has been released in 33 countries for on farm production. The success of IR8 in raising the yield potential of rice was so convincing that rice breeders the world over immediately initiated breeding programs to develop short statured varieties. Most of the improved rice varieties developed after IR8 at IRRI and by the national rice improvement programs have short stature and are responsive to nitrogenous fertilizers (Khush 1995).

Short growth duration

Most traditional varieties in tropical and subtropical Asia matured in 160–170 days and many were photoperiod-sensitive. These were suitable for growing one crop of rice a year during rainy season but were not suitable for multiple cropping systems. The growth duration has been progressively reduced. IR8, IR20 and IR26 mature in 130 days; IR28 and IR36 in 110 days and IR50 and IR58 in 105 days. The yield of short-duration varieties is equal to or higher than those of medium duration varieties but their per day productivity is much higher. The availability of short-duration varieties had led to major increases in cropping intensity, greater or farm employment, increased food supplies and higher food security in Asian countries (Khush 1987).

Superior grain quality

Grain quality in rice means different things to different people. Most consumers in the tropics and subtropics prefer long or medium long and slender grains. However, in temperate areas of Asia such as Northern China, Japan and Korea, preference is for short, bold and roundish grains. Cooking quality is determined largely by the amylose content and geletinization temperature of rice starch. In the tropics and subtropics, soft cooking but non-sticky varieties with intermediate amylose content and intermediate gelatinization temperature are preferred. In temperate areas, however, preference is for sticky cooking rice with low amylose content and low gelatinization temperature. Improved varieties developed in 1960s and 1970s had high amylose content and low gelatinization temperature and low acceptability. However, varieties developed in 1980s and 199s have intermediate amylose and intermediate gelatinization temperature and have higher acceptability. Widescale adoption of IR64 in Asia is due to its high palatability (Khush 1995).

Mutiple disease and insect resistance

With the introduction of high yielding varieties, farmers started using improved cultural practices such as the application of fertilizers and using higher plant populations per unit area. Development of irrigation facilities and availability of short duration varieties enabled farmers in tropical Asia to grow successive crops of rice throughout the year. These practices increased the vulnerability of the rice crop to disease and insect attacks. Chemical control of diseases and insects for prolonged periods in tropical climate is impractical. The use of host plant resistance for disease and insect control is the logical approach to overcome the production constraints. Therefore, major emphasis was placed on developing rice varieties with multiple resistance to major diseases and insects. While varieties developed in the 1960s and 1970s were susceptible to most diseases and insects, those developed later have multiple resistance to as many as four diseases and four insects (Khush 1989).

Large-scale adoption of varieties with multiple resistance has helped stabilize and increase world rice production. Yields of original high yielding varieties such as IR8 would have declined an average of 1.3% a year or a total of about 2 tons per hectare in 20 years without continuous crop improvement. Availability of multiple resistant varieties reduced the need for application of agrochemicals and facilitated the adoption of integrated pest management practices.

Tolerance for abiotic stresses

Large areas of land suitable for growing rice remain unplanted because of severe nutritional deficiencies and mineral toxicities. Even the well-managed ricelands suffer from mild nutritional imbalances. Moderate to high levels of tolerance for several nutritional disorders such as alkalinity, salinity, peatiness, zinc deficiency and iron and boron toxicities. Moderate levels of tolerance to these stresses have been incorporated into several improved varieties. For example, IR36, IR42, IR64 and IR74 have broad-spectrum tolerance for such stresses (Khush 1995).

Desirable traits combined

For widespread acceptance, several desirable traits such as high yield, short growth duration, multiple resistance to diseases and insects, superior grain quality, and tolerance for abiotic stresses have been combined into many improved varieties. IR36 released in 1976, was the first such variety. It has high yield, matures in 110 days, has excellent long slender grains, multiple resistance to diseases and insects and tolerance for abiotic stresses. Because of the desirable combination of these adaptive traits, it was accepted widely and became the most widely planted variety of rice or any other food crop the world has ever known. It was planted to 11 million ha of ricelands worldwide in 1980s (IRRI 1985). IR64, another variety with most of the desirable adaptive traits and even more palatable grains replaced IR36 during 1990s and is now the most widely grown variety of rice. It is planted to about 8 million hectares of riceland.

Impact on rice production

To date, about 600 rice varieties have been selected by national rice improvement programs from the improved breeding materials developed at IRRI. IRRI varieties and breeding lines have been used extensively as parents in the national rice improvement programs. It is estimated that IRRI bred varieties and their progenies are now planted to about 60% of the world's riceland. The gradual replacement of traditional varieties by improved ones, together with associated improvement in farm management practices, has had a dramatic effect on the growth of rice production, particularly in Asia. Farmers get 5–7 tons of paddy rice per hectare from high yielding varieties compared with 1–3 tons from traditional varieties. Since 1966 when the first high yielding variety of rice was released, the rice harvested area has increased only marginally, from 126 to 152 million hectares (18%) while the average yield has increased from 2.1 to 3.7 tons per hectare (76%). World rice production increased from 257 million tons to 600 million tons in 2000. Most of the rice growing countries became self-sufficient in rice.

The increase in per capita availability of rice and the decline in the cost of production per ton of output contributed to a decline in real price of rice, both in international and domestic markets. The unit cost of production is about 20–30% lower for high yielding varieties than for traditional varieties of rice and price of rice adjusted for inflation is 40% lower now than that in mid 1960s (Fig. 2). The decline in food prices has benefited the urban poor and the rural landless, who are not directly

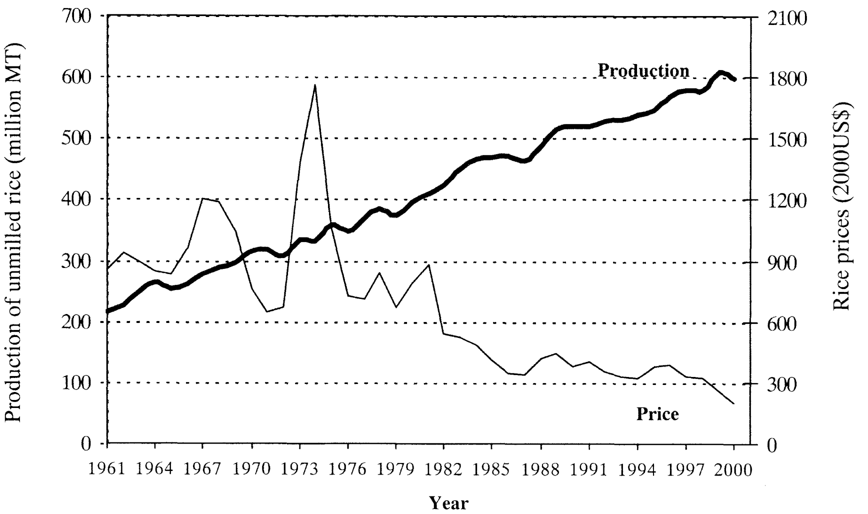

Fig. 2. Trends in world rice production and price, 1961–2000.

Source: Production: FAOSTAT Electronic Database, May 31 2001.

Rice Price: Relate to Thai rice 5%–broken deflated by G-5 MUV Index deflator

Source: World Bank Quarterly Review of Commodity Markets involved in rice production but who spend more than half of their income on food grains (Khush 1999).

The widespread adoption of high yielding varieties has helped most Asian countries to meet their growing food needs from productive lands and, thereby, has reduced the pressure to open up more fragile lands. Had 1962 yields still prevailed today, two times more lands in China and three times more lands in India would be needed to equal 1992 rice production. If Asian countries attempted to produce a 1990 harvest at yield levels of 1960s, most of the forests, woodlands, pastures and range lands would have disappeared and mountain sides eroded, with disastrous consequences for the upper water shed and productive lowlands, extinction of wild life habitats, and destruction of biodiversity (Khush 1999).

The availability of rice varieties with multiple resistance to diseases and insects reduced the need for application of agrochemicals and facilitated the adoption of integrated pest management practices. Reduced insecticide use has resulted in (1) enhanced environmental quality, (2) improved human health in farming communities, (3) availability of safer food and (4) protection of useful fauna and flora.

Distribution, exchange and evaluation of germplasm

From the inception of IRRI's rice improvement program, the germplasm has been freely shared with the national rice improvement programs. Seeds of donor varieties, early generation breeding materials, fixed elite lines and named varieties are sent to national program scientists at their request and through international nurseries. Thus seeds of breeding materials have been sent to 87 countries irrespective of geographical location or ideology. IRRI even shoulders the cost of shipment. These materials are evaluated for adaption to local conditions. Some are released as varieties and others are used as parents in the rice breeding program. As mentioned earlier, more than 600 IRRI bred lines have been released as national varieties in Asia, Africa and Latin America for the four rice ecologies.

Since 1975, germplasm has also been exchanged and evaluated through international nurseries conducted by International Network for Genetic Evaluation of Rice (INGER). These nurseries are composed of IRRI breeding lines, named varieties and donor parents. National programs are requested to nominate their best entries to these nurseries. These nursery sets are distributed to national programs upon their request. Various nurseries are composed for international evaluation for yield, resistance to diseases and insects and tolerance to abiotic stresses. They are an excellent means by which germplasm can be exchanged among different national and international programs. Thus materials developed in one country can be shared and evaluated in another country. For example, varieties released in Brazil, Burkina Faso, China, Myanmar, Nepal and Vietnam were bred in nine or more other countries. A total of 349 breeding lines selected from INGER nurseries have been released as 525 varieties (some lines are released in more than one country) in 62 countries (Chaudhary *et al.* 1998).

Training and staff development

The training program for familiarizing rice breeders from national programs was initiated in 1962. Since then, more than 1, 000 rice breeders have received training at IRRI. The periods of training have varied from a few months to 4 years. A large proportion of trainees participate in non-degree training programs. Between 1975 and 1986, more than 400 trainees participated in a Genetic Evaluation and Utilization Training Course. Other training courses have been organized on hybrid rice, molecular breeding, wide hybridization and biotechnology.

The degree training programs have been conducted in cooperation with the University of Philippines at Los Baños or universities in the country of trainees. Trainees complete course work in their own universities or at the University of Philippines and conduct thesis research with one of the IRRI staff members. To date, more than 100 students have received M. Sc. or Ph. D degrees under these collaborative training programs. Approximately 50 post-doctoral and visiting scientists have worked in plant breeding for duration of one to three years.

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