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Rice breeding: Past, present and future

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I am greatly honored by my selection for this prestigious prize. I express my sincere appreciation to the Japan Science and Technology Foundation for considering me worthy of this award.

I have been extremely fortunate to have been able to work with a team of dedicated agricultural scientists at the International Rice Research Institute (IRRI) and with dozens of national scientists in rice-growing countries. Such cooperation has resulted in the development of a series of high yielding varieties with disease and insect resistance and early maturity that are now planted on millions of hectares of rice land in Asia, Africa, and Latin America.

Rice was first domesticated in southern China and northeastern India – probably independently – about 8,000 years ago. Constant human selection for improved traits has modified domesticated rice varieties from their wild progenitors so much that domesticated rices can no longer survive in the wild state. The simple acts of reaping and sowing, for example, are selective. Primitive humans may not have known it, but they started the first rice breeding programs when they began to grow rice plants for their own use. Most primitive farmers have a keen eye and a sensitive feeling for plants. Millions of rice farmers have applied this keen insight and sensitivity for thousands of years to select better varieties.

Selection was first practised on the variable and heterogeneous wild and semi-wild populations, which must have narrowed genetic variability. However, several mechanisms in primitive agriculture, such as the introduction of varieties from one region to another and occasional natural crosses enhanced variability for further selection. Natural crosses between the domesticated crop and the weed complexes were another source of variability. The third source of variability was the varietal mixtures that primitive agriculturists grew as a protection against disease epidemics. Occasional intercrosses between component varieties gave still more variability. This conscious and unconscious selection by humans led to the development of over 150,000 varieties grown around the world.

The foundations of modern plant breeding were laid between 1700 and 1900. The 1694 discovery of sex in plants and hybridization beginning in 1719 paved the way for the artificial creation of variability. During this period, scientists proposed the

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"cell theory" and discovered the existence of the nucleus, chromosomes and reduction division to produce gametes and fertilization. The phenomenon of sterility was noted in interspecific crosses and the inheritance of characters was studied. Darwin's books, *The Origin of Species by Means of Natural Selection* and *The Effects of Cross and Self Fertilization in the Vegetable Kingdom*, enhanced interest in plant breeding.

The scientific basis of plant breeding has been enhanced tremendously during the 20th century. New breakthroughs have resulted in refinements of the two phases of plant breeding: the evolutionary phase (creation of variability) and the evaluationary phase (selection of superior combinations).

The rediscovery of Mendel's Laws in the first decade of the 20th century elucidated the mechanism of segregation of traits and the laws of inheritance. In the second decade, Morgan and his colleagues mapped *Drosophila* chromosomes, thereby explaining the linkage and recombination of traits. Vavilov established a germplasm collection of cultivated species and their wild relatives – the world's first "gene bank" – in the third decade. This was the forerunner of today's germplasm banks, which supply the "genetic building blocks" for modern crop breeding programs. Developments in cytogenetics during the fourth decade of this century, improved our understanding of the structure and functions of chromosomes, the mechanisms of recombination, and the relationships of species. In the fifth decade, the discovery of colchicine provided scientists a new tool in chromosome manipulation. The potential of X-rays in generating new variability was the greatest discovery of the sixth decade. Techniques for inducing gene mutations have become powerful tools for the plant breeder. Developments in biometrical and quantitative genetics in the seventh decade have helped plant breeders formulate selection strategies and conduct stability analyses.

Farmers themselves were responsible for most rice improvement from the time of its domestication to about 1900. The best-known examples are the "rono" varieties such as "Shinriki" that Japanese farmers selected in the 1890s. The rono varieties were shorter and therefore responded to nutrient inputs with higher yields. Rice breeding stations were established in China, India and Japan in the early 20th century. Rice breeders' initial activities were the purification of existing varieties through pureline selection. Some crossbreeding, or hybridization, was done, but varieties of hybrid origin had little impact until the 1950s. In 1949, the International Rice Commission (IRC) established a breeding program with headquarters at Cuttack, India, to cross tall tropical "indica" varieties with shorter "japonicas" from Japan and other regions of Eastern Asia. Most of these "North-South" combinations failed, but some varieties developed through the (IRC), such as Mahsuri and ADT 27, are still popular farm varieties in South and Southeastern Asia.

In 1956, agricultural scientists in Taiwan, China, released Taichung Native 1 – the first semidwarf rice variety to cross national boundaries in the tropics. TN1 was the progeny of a cross of Dee-geo-woo-gen, a dwarf rice from China, and a local variety. Because of its resistance to lodging when fertilized, TN1 was widely grown in India during the mid 1960s.

Despite the impact of varieties such as TN1, Mahsuri, and ADT 27, rice farmers in tropical and subtropical Asia grew hundreds of thousands of unimproved or semi-improved varieties even in the early 1960s, and few had been touched by modern agricultural science. These varieties were tall and weak-stemmed, and were late maturing. Most were sensitive to photoperiod or daylength, so they could only be grown in limited geographical regions. Such varieties, if resistant to one or two specific local diseases and insects, were invariably susceptible to those from neighbouring areas. Average yields in most tropical rice-growing nations were from 1 to 2 tons per hectare.

In the late 1950s and early 1960s, populations in these countries were increasing faster than food production. Because of these trends, several authorities such as Paddock and Paddock (1967) and Borgstrom (1972) predicted large-scale famines in the late 1970s. However, recent advances in wheat and rice breeding have produced varieties with a yield potential 2–3 times higher than that of the traditional varieties. These new varieties respond better to modern agronomic practices. Wide-scale adoption of these varieties and proper agronomic practices have led to major increases in food production World rice production increased 82% – from 257 million tons in 1965 to 468 million tons in 1985. World wheat production increased 89% from 267 million tons in 1965 to 506 million tons in 1985. As a result of the Green Revolution ushered in by improved rice and wheat varieties we now have 450 million tons of food grain reserves worldwide. Thus, instead of food scarcity and famines we have problems associated with overproduction, such as storage of surplus grain and crashing of prices.

Despite this overproduction, people in certain regions cannot afford adequate amounts of food. The Green Revolution technology has bypassed certain regions. The world population is likely to double in the next 40 years and we must double our food production in the same period.

I shall now attempt to review the major advances that have taken place in rice breeding leading to the Green Revolution in rice farming, and the challenges which lie ahead.

Recent achievements in rice breeding

The International Rice Research Institute (IRRI) was established in 1960 to apply science to agriculture to increase the production of rice, which forms more than half of the total food consumed by one out of three persons on earth. In 1962, IRRI scientists crossed Dee-geo-woo-gen, the same Chinese variety which had given TN1 its semidwarf plant stature, with Peta, a vigorous variety from Indonesia. In late 1966, IRRI released the variety IR8 from this cross. Because of its superior yield potential, IR8 was widely accepted. Other improved varieties were developed in succession.

The improved rice varieties which are now planted on 60% of the world's riceland have many desirable features which were not present in the pre-Green Revolution varieties. These features are 1) high yield potential, 2) short growth duration, 3) multiple disease and insect resistance, 4) superior grain quality, 5) tolerance for problem soils.

Yield potential

Rice varieties cultivated by farmers in the tropics and subtropics in the pre IR8 era were tall and leafy with weak stems, and had a harvest index (ratio of dry grain weight to total dry matter) of 0·3. When nitrogenous fertilizer was applied at rates exceeding 40 kg/ha, many traditional varieties tillered profusely, grew excessively tall, lodged early, and yielded less than they would with lower fertilizer inputs. To increase the yield potential of tropical rice, it was necessary to improve the harvest index and increase lodging resistance and nitrogen responsiveness. This was accomplished by reducing the plant stature through incorporation of a recessive gene for short stature from a Chinese variety Dee-geo-woo-gen. IR8 also had a combination of other desirable features such as heavy tillering, dark green and erect leaves, and sturdy stems. It responded to nitrogen fertilizer much better than traditional varieties such as Peta (figure 1). It had a harvest index of 0·5 and it doubled the yield potential of tropical rice. It was photoperiod-insensitive and had a growth duration of 130 days. Thus, in the tropics it could be planted any time of the year.

The IR8 plant type concept was so convincing and revolutionary that all the rice improvement programs immediately initiated crossing programs to develop short-statured varieties. Since then, more than 500 short-statured varieties have been developed by IRRI and national rice improvement programs, which are now planted on most of the irrigated and favorable rainfed lowland areas. During the 20-year period 1966–86, short-statured rice varieties were adopted on 60% of the riceland. Perhaps no other innovation in agriculture has had this wide acceptance.

Short growth duration

Most traditional varieties in tropical and subtropical countries mature in 160–170 days and many are photoperiod-sensitive. These were suitable for growing one crop of rice a year during the rainy season but not for multiple cropping systems. IR8 and subsequent varieties such as IR20 and IR26 mature in about 130 days. However, if the farmers grow 130-day-duration varieties, it is not possible to grow

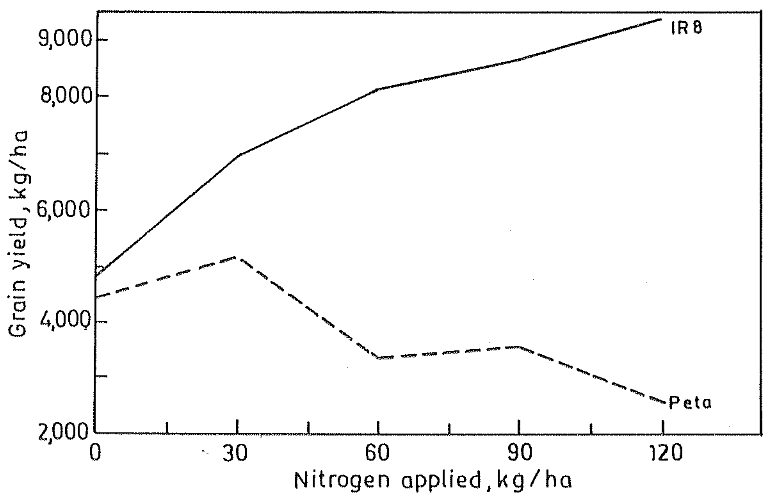

Figure 1. Nitrogen response of Peta and IR8 during 1966 dry season at IRRI.

another crop after rice or a second crop of rice in one rainy season. Therefore, major emphasis was placed on developing improved varieties with shorter growth durations. IR28 and IR30 developed in 1974 and IR36 developed in 1976 mature in 110 days. The growth duration was further reduced to 105 in IR50 and 100 days in IR58. However, yield is the primary consideration in the varietal development program. During the selection process, only those short-duration lines with yield potential that matched that of medium-duration varieties were saved. The key to the success of this program was the selection of genotypes with rapid vegetative vigor at earlier growth stages (Khush 1987). Because of higher growth rates at earlier stages, the short-duration varieties such as IR36, IR50, or IR64 are able to produce approximately the same total biomass in 85–90 days as the medium-duration varieties do in 115–120 days. Moreover, the harvest index of short-duration varieties is slightly better than that of the medium-duration varieties. Under most situations, the yields of early and medium growth duration varieties are similar.

However, because the short-duration varieties produce the same amount of grain in fewer days than medium-duration varieties, their productivity per day is much higher. In replicated yield trials at IRRI, IR64 produced 88 kg/day during the 1984 dry season and 54 kg/day in the wet season (table 1). IR42 yielded 68 kg/day in the dry season and 39 kg/day in the wet season.

Short-duration varieties are excellent for input economy. Because they grow rapidly during the vegetative period and are thus more competitive with weeds, weed control costs are reduced. Pesticide requirements are also minimized. And because the field duration of these varieties is 25–30 days shorter, they utilize less irrigation water, thus lowering production costs.

The availability of short-duration varieties has led to major changes in cropping patterns in Asia. In the Philippines, many farmers grow an upland crop either

Table 1. Yield of promising short-duration lines and varieties. IRRI, 1984 dry and wet seasons.

Selection	Growth duration (days)	1984 DS		1984 WS	
		Total yield (t/ha)	Yield per day (kg)	Total yield (t/ha)	Yield per day (kg)
IR 19743–46–2–3–3–2	98	5·6	73	4·2	54
IR 29658–69–2–1–2	107	6·8	79	4·8	56
IR 29658–94–2–1–3	107	7·4	86	4·9	57
IR 29725–22–3–3–3	108	7·1	82	3·8	44
IR 31802–48–2–2–2	106	6·7	79	3·6	42
IR 31851–63–1–2–3–2	106	7·6	89	3·6	42
IR 31868–64–2–3–3–3	110	7·1	80	4·2	47
IR 32307–107–3–2–2	110	7·3	82	4·1	46
IR 32429–47–3–2–2	105	7·6	90	5·7	68
IR 58	100	6·5	82	4·6	58
IR 36	110	7·2	81	4·4	49
IR 64	110	7·9	88	4·8	54
IR 42 (check)	135	7·8	68	4·5	39

before or after rice under rainfed conditions. In some areas, two crops of rice are regularly grown during the rainy season (figure 2). In Iloilo province, for example, 70% of the rainfed area is double-cropped with rice. Farmers grow three crops in irrigated areas. In Indonesia, where IR36 and other short-duration varieties have been widely adopted, the area under rice double cropping has increased rapidly. These changing cropping patterns have resulted in increased food supplies, higher food security, and more opportunities for on-farm employment for Asian farmers.

Many national rice improvement programs have also developed short-duration varieties. Ratna, Cauvery, and TKM9 in India, BG34–7 and BG367–7 in Sri Lanka, and Chandina in Bangladesh are well-known.

Multiple disease and insect resistance

Major changes have occurred in the varietal composition and cultural practices for rice during the post-IR8 era. A relatively small number of improved varieties have literally replaced thousands of traditional cultivars, thereby reducing the genetic variability of the crop. Farmers have started using improved cultural practices, such as application of more fertilizers and establishment of higher plant populations per unit area. Development of irrigation facilities and availability of short-duration, photoperiod-insensitive varieties have enabled the farmers in tropical Asia to grow successive crops of rice throughout the year.

Reduced genetic variability, improved cultural practices and continuous cropping with rice have increased the genetic vulnerability of the crop. Chemical control of diseases and insects for prolonged periods in tropical climates is very expensive and impractical. The use of host-resistance for disease and insect control is the logical approach to overcome these production constraints. Therefore, IRRI's rice improvement program has placed major emphasis on developing germplasm with

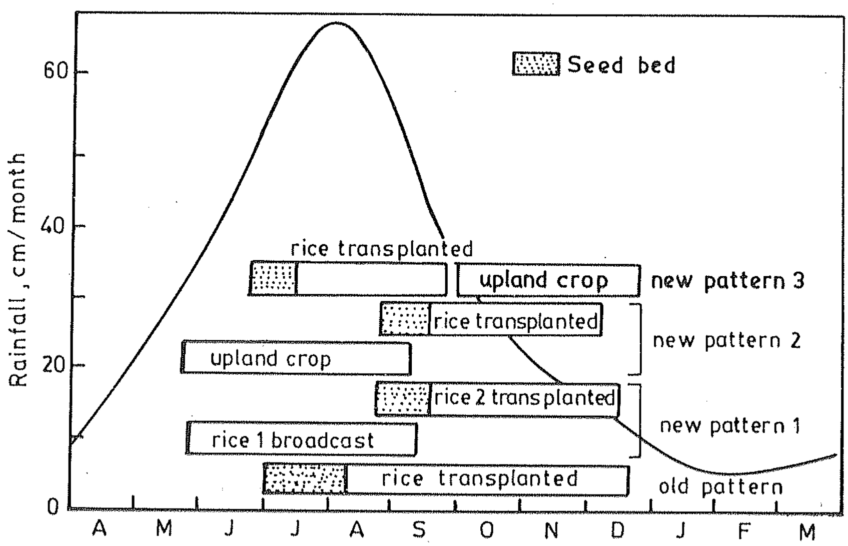

Figure 2. Schedule of old and new cropping patterns in the Philippines superimposed on rainfall pattern.

multiple resistance to major diseases and insects. Many national programs have similarly given priority to developing varieties with multiple disease and insect resistance.

Five diseases (blast, bacterial blight, sheath blight, tungro, grassy stunt) and four insects (brown planthopper, green leafhopper, stem borers, and gall midge) are a common occurrence in most countries in tropical and subtropical Asia. Breeding programs are focusing attention on developing germplasm with multiple resistance to these major diseases and insects.

For a host-resistance program to succeed, there must be donors for resistance. Thus, we need a large germplasm collection to identify donors. We need techniques for evaluating the germplasm to identify the donors and to screen the segregating populations. Finally, we need interdisciplinary cooperation between breeders, plant pathologists, and entomologists for rapid progress.

Fortunately, IRRI and national rice improvement programs have assembled excellent collections of rice germplasm. Pathologists and entomologists have developed screening techniques and many donors for resistance have been identified (Khush 1977). Utilizing these donors, we have developed improved varieties with resistance to as many as four diseases and four insects. The IRRI varieties IR5, IR8, IR22, and IR24 were susceptible to most of the diseases and insects. The first variety with multiple resistance was IR26, released in 1973. Since then many varieties with multiple resistance have been developed at IRRI and by the national programs. Table 2 shows the disease and insect ratings of the IR varieties.

Large-scale adoption of varieties with multiple resistance has helped stabilize world rice production. The value of multiple resistance in imparting yield stability is illustrated in figure 3. As this figure shows, the yield of susceptible IR8 fluctuates from year to year. If there is a disease or an insect attack, the yield is drastically reduced. However, if the disease or insect incidence is low, the yield is high. On the other hand, varieties with multiple resistance such as IR36 and IR42 show only minor fluctuations in yield from year to year and thus have greater yield stability.

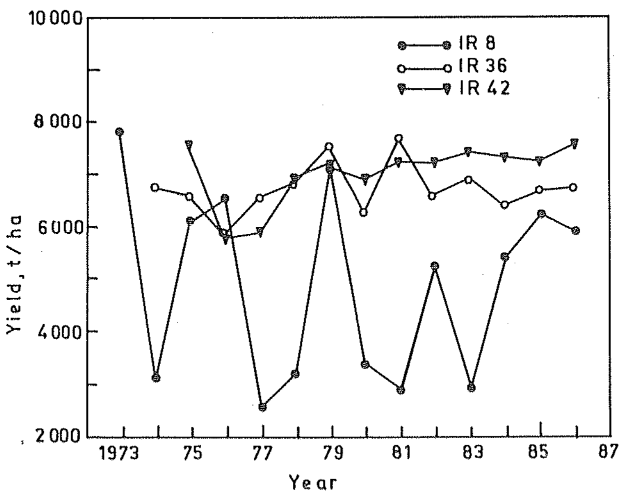

Figure 3. Yields of IR8 IR36, and IR42. Yields of multiple resistant IR36 and IR 42 show little year-to-year variation; yield of susceptible IR8 fluctuates widely. Dry season replicated yield trials at IRRI.

Table 2. Disease and insect resistance of varieties named by IRRI (IR5 to IR34) and of IRRI lines named as varieties by the Philippine Government (IR36–IR66).

IR variety	Reaction[a]									
	Blast	Bacterial blight	Grassy stunt	Tungro	BPH[b] biotypes			Green leaf-hopper	Stem borer	Gall midge
					1	2	3			
IR 5	MR	S	S	S	S	S	S	R	MS	S
IR 8	S	S	S	S	S	S	S	R	S	S
IR 20	MR	R	S	MR	S	S	S	R	MR	S
IR 22	S	R	S	S	S	S	S	S	S	S
IR 24	S	S	S	S	S	S	S	R	S	S
IR 26	MR	R	MR	MR	R	S	R	R	MR	S
IR 28	R	R	R	R	R	S	R	R	MR	S
IR 29	R	R	R	R	R	S	R	R	MR	S
IR 30	MS	R	R	MR	R	S	R	R	MR	S
IR 32	MR	R	R	MR	R	S	R	R	MR	S
IR 34	R	R	R	R	R	S	R	R	MR	S
IR 36	R	R	R	R	R	R	S	R	MR	R
IR 38	R	R	R	R	R	R	S	R	MR	R
IR 40	R	R	R	R	R	R	S	R	MR	R
IR 42	R	R	R	R	R	R	S	R	MR	R
IR 44	R	R	S	R	R	R	S	R	MR	S
IR 46	R	R	S	MR	R	S	R	MR	MR	S
IR 48	R	R	R	R	R	R	S	R	MR	S
IR 50	MS	R	R	R	R	R	S	R	MR	S
IR 52	MR	R	R	R	R	R	S	R	MR	–
IR 54	MR	R	R	R	R	R	S	R	MR	–
IR 56	R	R	R	R	R	R	R	R	MR	–
IR 58	R	R	R	R	R	R	S	R	MR	–
IR 60	R	R	R	R	R	R	R	R	MR	–
IR 62	MR	R	R	R	R	R	R	R	MR	–
IR 64	MR	R	R	R	R	MR	R	R	MR	–
IR 65	R	R	R	R	R	R	S	R	MS	–
IR 66	MR	R	R	R	R	R	R	R	MR	–

[a]R = resistant, MR = moderately resistant, S = susceptible, MS = moderately susceptible; – = reaction not known. Reactions were based on tests conducted in the Philippines for all diseases and insects except for gall midge which was conducted in India. [b]BPH = brown planthopper.

Grain quality

Grain quality in rice is dependent on milling recovery, grain size, shape, and appearance, and cooking characteristics. Higher milling recovery is a universal requirement and, to some extent, determined by the size, shape, and amount of chalkiness in the grain. Most consumers in the tropics and subtropics prefer long or medium long and slender translucent grains. Grain chalkiness (as in IR8) causes low milling recovery and poor consumer acceptance.

The cooking quality is determined largely by the amylose content and gelatinization temperature. In the tropics and subtropics, varieties with intermediate amylose content and intermediate gelatinization temperature are preferred. In the temperate areas of China, Korea, and Japan, however, rices of low amylose content and low gelatinization temperature are preferred.

Improved varieties like IR8 and IR5 have poor grain quality. They have bold, chalky grains which give very poor milling yields. The grains cook dry because of high amylose content, and have poor consumer acceptance. Improvement of milling recovery and grain appearance received immediate attention in the breeding program at IRRI. All the IR varieties released after IR5 and IR8 have slender and translucent grains and have very good milling recovery. However, improvements in the cooking quality were slow because all the donors for disease and insect resistance used in the hybridization program had high amylose content and low gelatinization temperature. The first improved variety with intermediate amylose content was IR48, but it has low gelatinization temperature. Similarly, several IR varieties such as IR20, IR32, IR36, and IR46, have intermediate gelatinization temperature but high amylose content. The first IR variety with a desirable combination of intermediate amylose content and intermediate gelatinization temperature is IR64 (table 3). It has been widely accepted as a high quality rice in Philippines, Indonesia, and Vietnam. Its grain quality is considered superior to that of the high quality traditional varieties such as C4-63, Azucena, and Milfore.

Another important quality characteristic by which premium quality rices are known is their pleasant aroma. None of the improved varieties are aromatic. However, several improved breeding lines with aromatic properties have been developed and are being evaluated in replicated yield trials. It is hoped that we will soon have improved aromatic varieties.

Tolerance to problem soils

Millions of hectares of lands suitable for growing rice remain unplanted because of severe nutritional deficiencies and toxicities. Even well-managed ricelands suffer from mild nutritional deficiencies or toxicities. For example, Zn deficiency in rice soils is becoming a common concern in many countries. A vast majority of rice soils have varying levels of salinity or alkalinity. Several improved varieties have been developed which have moderate to high levels of tolerance for several nutritional deficiencies and toxicities. IR36, for example, has tolerance for salinity, alkalinity, peatiness, and iron and boron toxicities. It is also tolerant of Zn deficiency (IRRI 1982). IR42 similarly has a broad spectrum of tolerance for many soil problems (table 4). Varieties tolerant of these deficiencies and toxicities have a more stable performance and do well across several locations. As shown in figure 4, IR36 and IR42 consistently yield better than IR8 at all levels of fertility. This superior performance is largely attributed to the broad-spectrum tolerance of IR36 and IR42 for problem soils.

Combination of favorable traits

For large-scale adoption, a variety must have a favorable combination of traits. High yield or early maturity alone, for example, is not enough. Therefore, we have

Table 3. Main characteristics of IR varieties.

Variety	Environment suited for	Growth duration (days)	Height (cm)	Amylose content	Gelatinization temperature	Grain size and shape
IR 5	Rainfed	140	130	High	Intermediate	Medium, medium
IR 8	Irrigated	130	100	High	Low	Long
IR 20	Irrigated	125	110	High	Intermediate	Medium, medium
IR 22	Irrigated	125	90	High	Low	Long, slender
IR 24	Irrigated	120	90	Low	Low	Long, slender
IR 26	Irrigated	130	100	High	Low	Medium, medium
IR 28	Irrigated	105	100	High	Low	Long, slender
IR 29	Irrigated	115	100	Glutinous	Low	Long, slender
IR 30	Irrigated	110	100	High	Intermediate	Medium, medium
IR 32	Irrigated	140	105	High	Intermediate	Long, slender
IR 34	Irrigated	130	125	High	Low	Long, slender
IR 36	Irrigated	110	85	High	Intermediate	Long, slender
IR 38	Irrigated	125	100	High	Intermediate	Long, slender
IR 40	Irrigated	120	100	High	Intermediate	Medium, medium
IR 42	Irrigated	135	110	High	Low	Medium, medium
IR 43	Upland	125	110	Low	Low	Long, slender
IR 44	Irrigated	130	110	High	Low	Long, slender
IR 45	Upland	125	100	High	Intermediate	Long, slender
IR 46	Rainfed	130	110	High	Intermediate	Long, slender
IR 48	Irrigated	140	120	Inter-mediate	Low	Long, slender
IR 50	Irrigated	105	90	High	Intermediate	Long, slender
IR 52	Rainfed	115	95	High	Low	Long, slender
IR 54	Irrigated	120	95	High	Low	Long, slender
IR 56	Irrigated	110	90	High	Low	Long, slender
IR 58	Irrigated	100	80	High	Low	Medium, medium
IR 60	Irrigated	108	95	High	Low	Long, slender
IR 62	Irrigated	115	110	High	Intermediate	Medium, medium
IR 64	Irrigated	115	105	Inter-mediate	Intermediate	Long, slender
IR 65	Irrigated	115	105	Glutinous	Low	Long, slender
IR 66	Irrigated	110	100	High	Intermediate	Long, slender

endeavored to combine most of the desirable traits into the same variety. IR36 released in 1976 was the first product of such an effort. It has excellent yield potential and a harvest index of 0·55. It matures in 110 days, and has excellent long, slender grains, multiple resistance to major diseases and insects, and tolerance for several nutritional toxicities and deficiencies. Because of these desirable attributes, it was accepted widely and became the most widely planted variety of rice or any other crop the world has known. During the early 1980s it was planted in 11 million hectares of riceland all over the world. It still is the most widely planted variety of rice in the world. It has been estimated that farmers who planted IR36 between 1980 and 1984 harvested 1 billion dollars worth of extra rice annually. An External Review Panel consisting of 12 eminent scientists examined the work of IRRI in 1981–82 and pointed out, "The impact of IR36 alone would more than justify the investment in IRRI since its establishment in 1960."

IR50, released in 1980, is another variety with a desirable combination of traits. It matures 5–7 days earlier and yields 10% more than IR36. However, its

Table 4. Reaction of some IR varieties to adverse soil conditions[a].

Variety	Toxicity					Deficiency	
	Salt	Alkali	Peat	Iron	Boron	Phosphorous	Zinc
IR 5	4	7	0	6	4	5	5
IR 8	3	6	5	7	4	4	4
IR 20	5	7	4	2	4	1	3
IR 28	7	5	6	4	4	3	5
IR 36	3	3	3	3	3	7	2
IR 42	3	4	5	3	2	3	4
IR 48	4	7	5	6	0	5	5
IR 64	3	3	4	5	4	4	4

[a]On a scale of 0–9: 0–no information; 1–almost normal plant; 9–almost dead or dead plant.

acceptance has been hampered because its resistance to blast "broke down" in certain areas. IR64, released in 1985, combines all the desirable traits of IR36 but has superior grain quality because of its intermediate amylose content and intermediate gelatinization temperature. It outyields IR36 by 20% and has horizontal resistance to blast. It is accepted widely in many countries.

Impact of modern varieties

To date, 30 improved IR varieties have been released by IRRI (IR5–IR34) and the Philippine Seedboard (IR36–IR66) . In addition, 154 varieties have been selected and released by the national rice improvement programs from IRRI-bred materials. About 350 improved rice varieties have been developed by the national rice

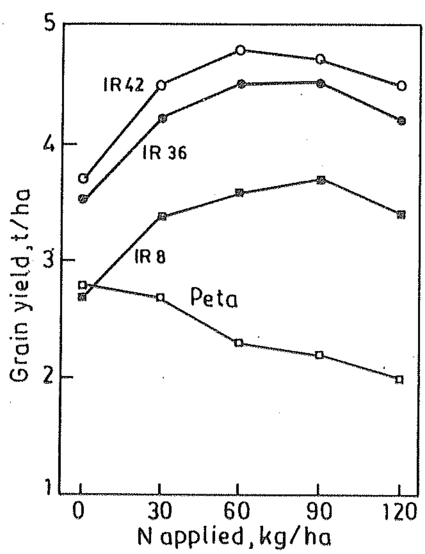

Figure 4. Grain yield response of 4 rices to different levels of nitrogen. Data are averages for IRRI and the three experiment stations of the Philippine Bureau of Plant Industry (Maligaya, Bicol, and Visayas), 1976–1985 wet seasons. (S K De Datta, IRRI–Agronomy Department, unpublished).

Table 5. Total area planted to rice and to improved varieties in selected Asian countries, 1986.

Country	Total area (million ha)	Area planted to improved varieties %
Bangladesh	10·1	28
Burma	4·6	53
China	33·2	98
India	41·2	53
Indonesia	9·8	77
Korea (South)*	1·2	95
Malaysia	0·7	70
Nepal	1·3	30
Pakistan	2·0	51
Philippines	3·2	90
Thailand	9·6	15
Vietnam	5·7	51
Sri Lanka	0·9	91

* Includes area planted to improved varieties of indica/japonica origin (25%) and improved japonica varieties (70%).

improvement programs. The improved rice varieties are now planted in 60% of the world's riceland. In China, Korea, Philippines, and Sri Lanka, more than 90% of the area is now planted to improved varieties (table 5). In Indonesia, India, Pakistan, Burma, Malaysia, and Vietnam more than 50% of the area is planted to such varieties. Because of large-scale adoption of improved varieties and associated management practices, rice production has dramatically increased in most of the major rice-growing countries (table 6).

The Asian rice belt, which used to be a rice-deficit area, has now more than 8 million tons of exportable surplus. Indonesia, which used to import up to 2 million tons of rice until the early 1980s, became self-sufficient in 1984 and had an exportable surplus in 1985 and 1986. Indonesian rice production increased

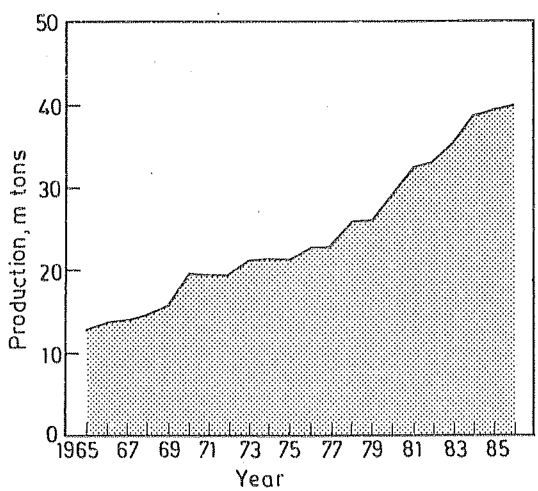

Figure 5. Impact of improved technology on Indonesian rice production.

Table 6. Rice production increases in selected Asian countries, 1965–85.

Country	Rice production (million tons)		% increase in 1985 over 1965
	1965	1985	
Bangladesh	15·7	22·5	143·3
Burma	8·0	14·5	181·2
China	92·0	171·3	186·1
India	45·9	96·3	209·8
Indonesia	12·9	39·1	302·3
Korea (South)	4·8	7·8	162·2
Malaysia	1·2	1·8	150·0
Nepal	2·2	2·8	127·2
Pakistan	1·9	5·0	263·1
Philippines	4·0	9·1	227·5
Thailand	11·1	19·5	175·6
Vietnam	9·8	15·8	161·1
Sri Lanka	0·8	2·3	287·5

threefold in a 20-year period – from 12.9 million tons in 1965 to 39·1 million tons in 1985 (figure 5). Rice yields in Indonesia increased from 1·76 t/ha in 1965 to 4·0 t/ha in 1985. In India, rice production doubled in a 20-year period from 45·9 million tons in 1965 to 96·3 million tons in 1985 (figure 6). In some states of India, rice production dramatically increased. In Punjab, for example, the average yield increased from 1·6 t/ha in 1965 to 5·0 t/ha in 1985. The area planted increased from 0·29 million ha in 1965 to 1·7 million ha in 1985. Rice production increased from 0·34 million tons in 1965 to 8·6 million tons in 1985, an increase of 24 times in a 20-year period (figure 7). Rice production in Punjab increased 14% per year. There is no parallel example of increased food production anywhere in the world.

Similar increases occurred in the Philippines where rice production increased from 4·0 million tons in 1965 to 9·1 millions in 1985 – 227·5% increase in a 20-year

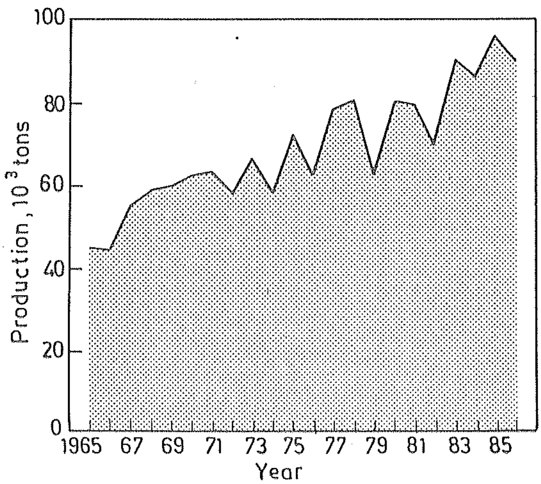

Figure 6. Impact of improved technology on Indian rice production.

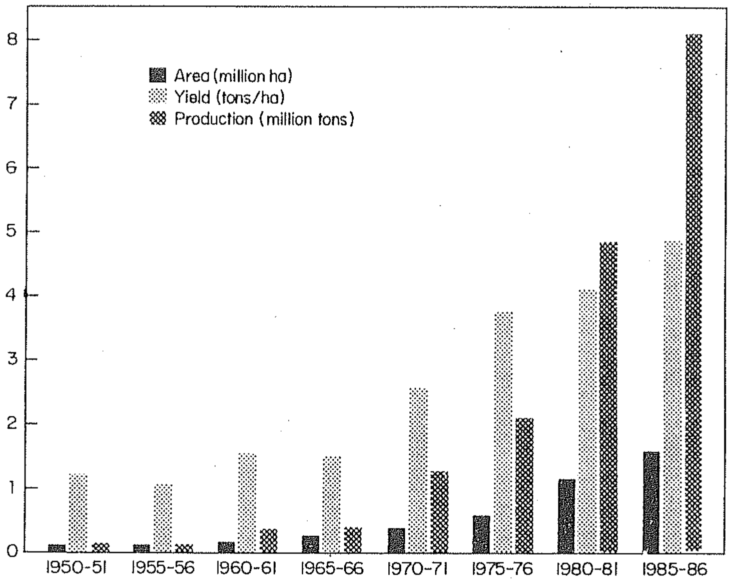

Figure 7. Area planted to rice, yield and production of paddy in Punjab, 1950–1985.

period (figure 8). This increase is entirely due to increased per hectare productivity as the cultivated area in 1965 and 1985 was about the same.

The major impact of the increased rice production has been the substantial decline in rice prices particularly from the late 1970s to the present. As shown in figure 9, the index of paddy production accelerated faster than the index of real prices for Burma, India, Indonesia, Philippines, Sri Lanka, and Thailand (Gonzales and Umali 1985). The real domestic prices in these countries declined steadily. Lower real prices clearly benefit the consumers – lower prices have income effects, that is the consumers can gain increasing purchasing power, and therefore, indirectly imply an improvement in their nutritional status.

The price of rice on the international market has similarly declined (figure 10), which is another measure of the success of new rice technology spearheaded by the improved varieties.

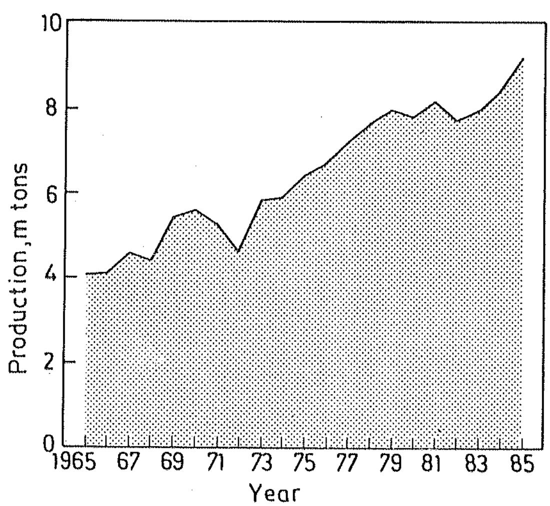

Figure 8. Impact of improved technology on Philippine rice production.

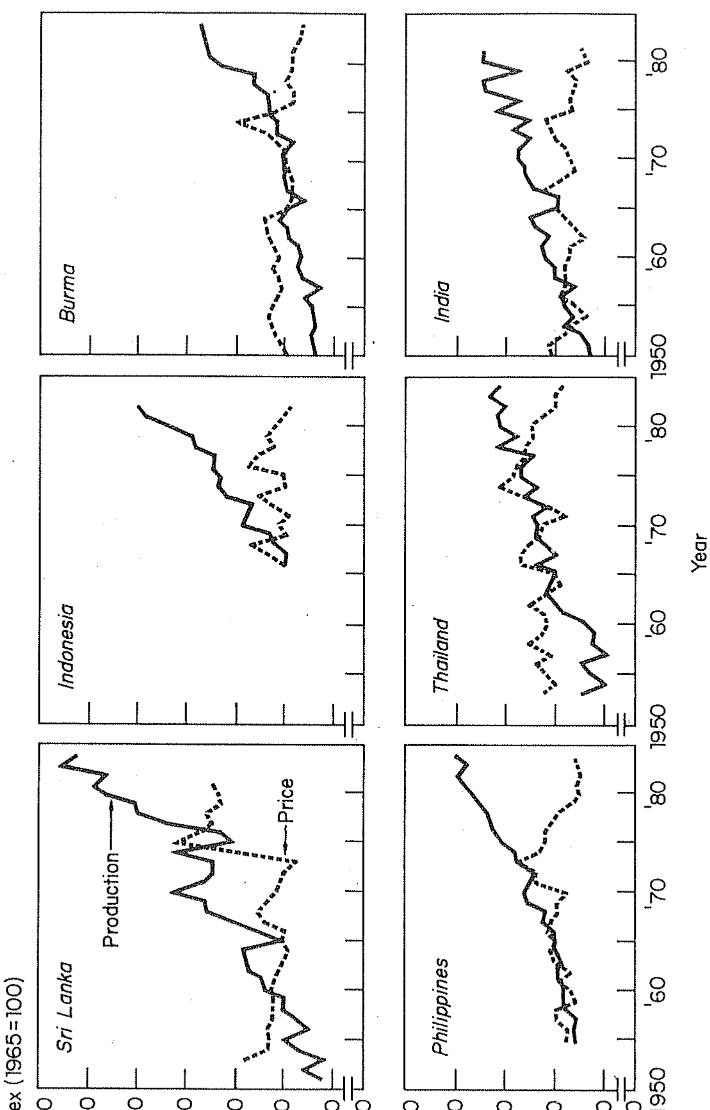

Figure 9. Trends in paddy production and farm price at constant prices in six major rice producing countries.

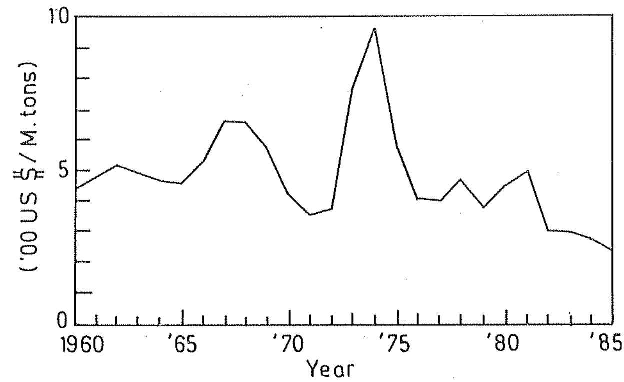

Figure 10. Rice export price at Bangkok (deflated)

Future challenges in rice breeding

The biggest challenge that rice scientists face today is how to continuously generate technology that will lead to increased production commensurate with increases in world population. It took perhaps one to two million years for the human population to grow to one billion, which it reached in about 1830. It required only 100 years to reach 2 billion by 1930 and the three billion figure was reached in 1960 in only 30 years. The 4th billion was added in 15 years (by 1975) and the 5th billion in 12 years (by 1987). Although the percentage of annual increase worldwide has fallen from 2·0 to 1·7% in the last 5 years, the annual increase in human numbers continues to rise at a frightening rate because of a larger population base. Each year there are 94 million new mouths to feed. As shown in figure 11, the world population is likely to reach 8 billion by year 2016 and

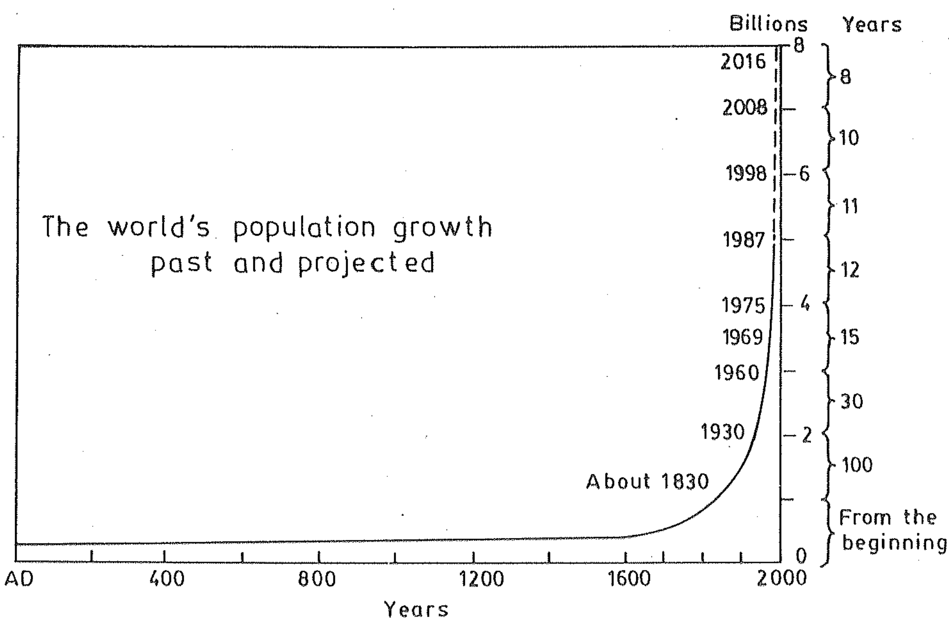

Figure 11. World's population growth, past and projected.

10 billion by 2030. It should be remembered that the population in the rice-consuming countries is increasing faster than in the rest of the world. The number of rice eaters will probably double during the next 30–35 years. Thus, rice production will have to be doubled by the year 2020. It has been estimated that the demand for rice will exceed production by the end of this century (IFPRI 1977).

Rice-growing environments are classified into five major categories (Khush 1984). Irrigated rice accounts for about 55% of the total area. Another 5% is favorable rainfed lowland where improved varieties and technology have been adopted. About 80% of the world rice production comes from 60% of these favorable rice-growing areas. However, very few varieties and little new technology have been developed for the unfavorable (rainfed lowland, upland, deepwater, and tidal wetland) environments. The challenges of rice improvement now therefore are twofold:

(1) For the favorable environments, to develop rice varieties with higher yield potential, yield stability, superior cooking quality and shorter growth duration.
(2) For the unfavorable environments, to develop improved varieties with higher productivity, yield stability, and with tolerance to environmental stresses.

Varietal development for favorable environments

Yield: Since the initial breakthrough in yield potential when IR8 was developed, there has been only marginal increase in yield potential, although per day productivity has been increased in the short-duration varieties. Our major challenge is to develop varieties with a quantum jump in yield over that of IR8.

Yield is a function of total dry matter and harvest index. Therefore, yield can be increased by increasing either the total dry matter or harvest index, or both. Rice physiologists believe that physical environment is not limiting for increasing the rice yield beyond current levels. Rice varieties with higher yield potential must retain the "good plant-type traits" namely, short stiff (lodging-resistant) culms, erect leaves, and high tillering ability. In addition, incorporating the following varietal traits should help increase rice yield per crop.

(1) Increased harvest index:
    a. Increased sink size:
        (i) large spikelet number per shoot with suitable spikelet size;
        (ii) greater partition of assimilates to spikelet formation.
    b. Increased spikelet filling:
        (i) manipulation of canopy senescence;
        (ii) higher quality grain percentage;
        (iii) maintenance of healthy root system;
        (iv) increased lodging resistance.
(2) Increased biomass production:
    a. Establishment of desirable canopy structure:
        (i) rapid leaf area devlopment;
        (ii) rapid nutrient uptake.
    b. Reduced carbon consumption.
(3) Increased canopy photosynthesis during entire growth period.

The yield increase in rice varieties developed so far through conventional breeding has been brought about primarily by improvement in plant type. Further improvement will be possible by specific selection for the traits enumerated. The inheritance of most of these traits is not clearly understood and genes controlling these traits and other desirable plant characteristics are likely to have both desirable and undesirable linkages. Any breeding approach that will allow retention of desirable genetic linkages, break the undesirable (repulsion phase) linkages and improve the selection efficiency in discriminating between high- and low-yielding genotypes should be helpful in developing varieties with higher yield potential. Innovative breeding methods such as heterosis breeding, recurrent selection, biparental mating and disruptive mating, and the anther culture method, aided by modified selection and evaluation procedures, should help meet the desired objectives.

Assuming that some undesirable genetic linkages limit the yield potential of the true breeding lines developed through conventional breeding, the F_1 hybrids should help overcome the effect of undesirable linkages by bringing the desirable dominant genes from two parents together. This approach has been successfully employed in China (Lin and Yuan 1980) and its utility in the tropics is being explored (Virmani *et al* 1981).

Recurrent selection is used primarily to promote recombination and to increase the frequencies of favorable genes for quantitatively inherited traits. It is cyclic, encompassing the two phases of plant breeding: a) selecting a group of genotypes that possess favorable genes, and (b) mating the selected genotypes to obtain genetic recombination (Frey 1982). The applicability of this technique to self-pollinated species has been limited because of technical problems of intermating. However, availability of monogenic male sterility (Singh and Ikehashi 1981) in rice variety IR36 has made it possible to use the recurrent selection technique for developing varieties with higher yield potential.

Biparental or disruptive mating schemes can also be employed to overcome the problem of adverse linkages. Biparental mating involves intermating of selected plants in F_2 so as to accumulate favorable genes and to break linkages, thereby releasing a greater reservoir of genetic variability to enable the breeder to exercise selection (Joshi 1979). Disruptive mating involves the intermating of unlikes in segregating generations. It leads to greater opportunity for crossing over, which releases latent variation by breaking repulsion phase linkages (Thoday 1960).

Plant breeders are often faced with the low efficiency of visual plant selection for yield in the early segregating generations. Heterogenous soil fertility conditions, intergenotypic competition due to density of the population, and micro and macroenvironmental effects are some factors responsible for low selection efficiency. Dominance and epistatic variance in the segregating populations reduce selection efficiency. Cultural methods such as high fertilizer rates and wider spacing, which allow for maximum expression of genotypes for yield and reduce the variability due to environmental factors, may be employed as aids to selection for higher yield potential. The haploid method using anther culture is also useful for improving the selection efficiency for yield and other traits of low heritability. In the doubled haploid lines there is more additive genetic variance as compared to the conventional F_2 and F_3 generations. In addition, dominance variance is eliminated. In F_3 and F_4, additive and dominance effects contribute to phenotypic differences between individuals, whereas variation in doubled haploid progeny is only due to microenvironmental effects (Snape 1982). Thus, selection efficiency in the doubled haploid population is likely to be higher when there is greater dominance variation in the cross.

Improvements in the yield potential of rice to date have been brought about primarily through selection for improved plant type following conventional methods of pedigree or backcross breeding. However, for further progress in increasing the yield potential, conventional breeding methods must be supplemented with the innovative breeding techniques discussed earlier.

Grain quality: Most improved varieties have excellent grain size, shape, and appearance, and good milling recovery. But most have high amylose content and low gelatinization temperature of the grain starch. It is now obvious that in the tropics and subtropics, there is universal preference for rices with intermediate amylose and intermediate gelatinization temperature. Fortunately, there seems to be no genetic barrier to combining these quality traits with high yield or other adaptability traits. Wide-scale acceptance of IR64 as a high quality rice fortifies our conviction that rices with intermediate amylose content and intermediate gelatinization temperature have superior palatability. Rice breeders should, therefore, endeavor to incorporate these desirable grain quality features in the future rice varieties.

Aromatic rices are valued by consumers and command higher prices. Yet this trait has not been incorporated into any of the improved rice varieties. Basmati rices of India and Pakistan have grain elongation traits in addition to aroma, and are sold at premium prices in national and international markets. Despite concerted efforts by several rice improvement programs during the last 20 years, high-yielding varieties with Basmati grain quality have not been developed. The challenge of developing high-yielding Basmati is a major one for rice breeders. The methods discussed earlier may prove useful in breaking the undesirable linkages that are hampering progress in this area.

Yield stability: Yield stability depends on multiple resistance to major diseases and insects. However, resistant varieties do not remain resistant forever. The useful life of a resistant variety is 5–10 years. We must endeavor to develop varieties with durable resistance. Polygenic resistance is assumed to be more durable. Recurrent selection procedures discussed earlier are helpful in accumulating polygenes for resistance in the same genotype. Thus, more attention will have to be paid to developing varieties with more durable resistance.

Wild species of rice are a rich source of genes for disease and insect resistance. However, this resource has not been exploited for rice improvement. We have recently succeeded in transferring genes for resistance to brown planthopper and whitebacked planthopper from *Oryza officinalis* to *O. sativa* across crossability and recombination barriers (Khush and Jena 1987). Other wild species also have useful genes for resistance and we may have to use the techniques of biotechnology, such as embryo rescue and protoplast fusion, to move these genes from the wild species to cultivated rice.

Through genetic engineering techniques, it is now possible to move genes from unrelated organisms to crops of economic importance. Transfer of the *Bt* gene from *Bacillus thuringiensis* to tobacco is an outstanding example of the potential of genetic engineering techniques in crop improvement. The *Bt* gene is expressed in the genetically engineered plants and produces the toxin which kills lepidopteran insects (Vaeck *et al* 1987). It is known that some plants such as neem (*Azadirachta indica*) produce chemicals that have insecticidal properties. Can we clone the neem gene or genes responsible for the production of these chemicals and transfer them to rice through genetic engineering techniques?

To date, sources of resistance to some important diseases such as sheath blight have not been found, although a large number of germplasm entries have been screened. Development of varieties resistant to sheath-blight is yet another challenge to plant breeders.

Shorter growth duration: Several varieties with a growth duration of 110 days have been developed whose yield potential is comparable to that of varieties with a 130-day growth duration. Can we develop varieties with a 90–95 day growth duration without reduction of yield potential? It is obvious that we will have to select genotypes with very fast growth rates so that they are able to produce the same biomass in fewer days. It has been observed that short-duration varieties have weaker stems. Can the linkage between short growth duration and straw weakness be broken?

Varietal development for unfavorable environments

Unfavorable environments (rainfed lowland, upland deepwater, tidal wetland) are characterized by variable water regimes, occurrence of drought, submergence, waterlogging, and soil toxicities or deficiencies. Progress in developing improved varieties for these environments has been extremely slow because:

- The ideal high-yielding plant type for various unfavorable environments is still not clearly defined.
- Adaptability of the genotypes for specific rice culture is most important. Hence it is essential to retain, as far as possible, the adaptability traits of the locally adapted varieties.
- Adaptability and productivity traits are sometimes negatively correlated, hence the problem of repulsion phase genetic linkages has to be overcome.
- Inheritance of adaptability traits such as drought-tolerance, submergence tolerance, elongation ability, and tolerance to mineral stresses is not adequately understood. Very little information is available on the mechanisms of tolerance to these stresses.
- Selection for local adaptability can be done only by screening and evaluating the breeding material in target areas.
- Available screening procedures for selecting for tolerance to various stresses do not give consistent results.
- The generation advance is slower because of the complexity of the evaluation procedures and involvement of photoperiod sensitivity in some populations.
- Suitable donors for certain stresses have not been identified.

To develop improved germplasm for the unfavorable environments, the following strategies will have to be followed.

(i) Definition and characterization of the major favorable rice cultural types and identification of the representative sites for selection and evaluation of breeding material. Considerable progress has been made in these directions but more needs to be done (Khush 1984).

(ii) Identification of donors for specific traits and varieties, adapted to various target environments.
(iii) If improvement is desired in a few traits, backcross or mutation methods of breeding may be employed using a locally adapted variety as the base.
(iv) If a large number of traits are to be improved simultaneously, the conventional pedigree method of breeding for handling crosses between locally adapted materials and donors for traits to be incorporated should be adopted.
(v) Population improvement methods of breeding using male sterile lines and facilitated recurrent selection should be employed to promote recombination and increase the frequency of favorable genes in the breeding populations.
(vi) Attempts should be made to improve the harvest index by selecting genotypes with larger sink size.
(vii) The Rapid Generation Advance (RGA) technique could be used extensively for selected crosses involving photoperiod-sensitive parents.
(viii) Tissue culture techniques may be employed to exploit somaclonal variation to select for stress tolerance.
(ix) Wide hybridization may be employed to incorporate traits for stress tolerance from the wild germplasm.
(x) A shuttle breeding approach may be adopted for screening and evaluating breeding material in cooperation with scientists working in target areas.

Conclusions

The Green Revolution technology, centered on high-yielding, disease- and insect-resistant rice varieties, has revolutionized rice production since the late 1960s. Many countries in the rice belt of Asia, which used to import large quantities of rice, have become self-sufficient and have some surpluses to export. As a result, rice prices on the international market and in the domestic markets of many countries have fallen, thus helping the purchasing power of weaker sections of these societies. The consequent improvement in food security has led to political stability and allowed the governments of the developing countries to pay more attention to the pressing needs of economic development.

Population growth is continuing at more than 2% annually in many developing rice-growing countries. The demand for rice is likely to exceed supply by the year 2000. To feed this growing population, the growth rate of rice production needs to accelerate further. For this we need varieties with higher yield potential, greater yield stability, shorter growth duration, and superior grain quality. Innovative breeding methods and the emerging techniques of biotechnology must supplement the conventional breeding methods in achieving the future rice breeding goals.

Rice breeding today is an international effort, involving scientists worldwide. IRRI is supported by an informal organization of 34 donor agencies called the Consultative Group on International Agricultural Research (CGIAR). The Government of Japan is the third largest donor to the CGIAR. Numerous Japanese scientists have made notable contributions to rice science and improvement. Half of the world's yearly scientific literature on rice science is published in Japan.

The recognition of IRRI's work by the awarding of the 1987 Japan Prize will help generate additional support for rice improvement in the developing nations. This in turn will help achieve the noble goals of "Peace and prosperity for all" set by the Japan Science and Technology Foundation.

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