Rice Biotechnology for Developing Countries in Asia

Edilberto D. Redoña
Philippine Rice Research Institute
Science City of Muñoz, Philippines

Rice (*Oryza sativa* L.) is the staple food for more than three billion people, over half the world's population. It provides 27% of dietary energy and 20% of dietary protein in the developing world. Rice is cultivated in at least 114, mostly developing, countries and is the primary source of income and employment for more than 100 million households in Asia and Africa (FAO, 2004). Of the 840 million people suffering from chronic hunger, over 50% live in areas dependent on rice production. About 80% of the world's rice is produced on small farms, primarily to meet family needs, and poor rural farmers account for 80% of all rice producers (FAO, 2004). Less than 7% of the world's rice production is traded internationally (Maclean *et al.*, 2002) and with this small marketable surplus, prices fluctuate widely with droughts, floods, and typhoons (Hossain, 1997).

Rice is the dominant crop in Asia where, in many countries, it covers half of the arable land used for agriculture (Cantrell and Hettel, 2004). The Asian continent, host to 56% of humanity including 70% of the world's 1.3 billion poor people, produces and consumes around 92% of the world's rice (Papademetriou, 1999). Nine of the top-ten rice-producing countries in 2003, namely, China, India, Indonesia, Bangladesh, Vietnam, Thailand, Myanmar, the Philippines, and Japan are in Asia. China and India combined account for more than half of the world's rice area, and, along with Indonesia, consume more than three-fourths of the global rice production (Hossain, 1997; Maclean *et al.*, 2002).

In addition to being the world's most popular staple—cultivated for more than 10,000 years—rice provides a symbol of global unity and cultural identity for many countries where its cultivation is intertwined with religious observances, festivals, customs, folklore, and other traditions. Cognizant of this, the United Nations launched the International Year of Rice in 2004 with the theme Rice is Life, the first time a year has been dedicated to a single crop, to underscore the enormous implications of rice for human nutrition, global food security, and alleviation of poverty (FAO, 2004).

THE CHALLENGE TO INCREASE RICE PRODUCTIVITY

Record rice-production increases occurred during the last three decades of the twentieth century, beginning with the Green Revolution. In many Asian countries, yield levels doubled or tripled from the pre-Green Revolution average of 1.9 tons per hectare (t/ha) (Figure 1). Between 1966 and 2000, populations of low-income countries increased by 90%, while rice production increased by 130% from 257 million tons (Mt) in 1966 to 600 Mt in 2000. Average per-capita food availability was 18% higher in 2000 than in 1966 (Khush, 2004). About 84% of the rice-production growth has been attributed to modern farming technologies such as varieties that are semi-dwarf, early maturing, non-photoperiod sensitive (and can, therefore, be planted more than once per year), and responsive to nitrogen (N) fertilizer (Maclean *et al.*, 2002). More than 2,000 modern varieties have been commercially released in twelve countries of South and Southeast Asia over the past 40 years (Cantrell and Hettel, 2004). Gradually, resistances and tolerances to biotic and abiotic stresses were incorporated into many of these varieties, thereby extending their cultivation and productivity potential. As a consequence, rice-production cost per unit output was reduced by 20 to 30%, which translated to reduced rice prices at the consumer level from about US$450/t unmilled rice in the early 1950s to less than US$300/t by 1999 (Maclean *et al.*, 2002). Furthermore, these productivity gains have allowed production to more than double and fulfill the demand of a population that grew by 80% in the same period. This has helped to reduce world market rice prices by 80% over the last 20 years (Cantrell and Hettel, 2004).

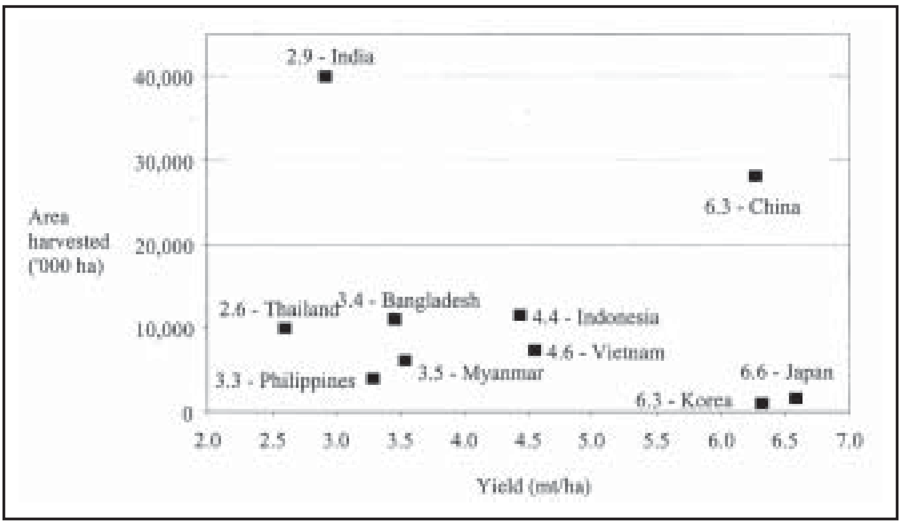

Figure 1. Area harvested and yield levels in major Asian rice-growing countries (FAO, 2004).

There is tremendous pressure, however, to further improve rice productivity in order for it to keep pace with population growth. In Asia, it is projected that demand for rice will increase by 70% over the next 30 years, driven primarily by population growth that, excluding China, is expected to increase by 51% (Hossain, 1997). The Asian population is expected to increase from 3.7 billion in 2000 to 4.6 billion in 2025 (Cantrell and Hettel, 2004). The urban population will nearly double from 1.2 billion to 2.0 billion, as people move from rural areas to the cities in search of employment.

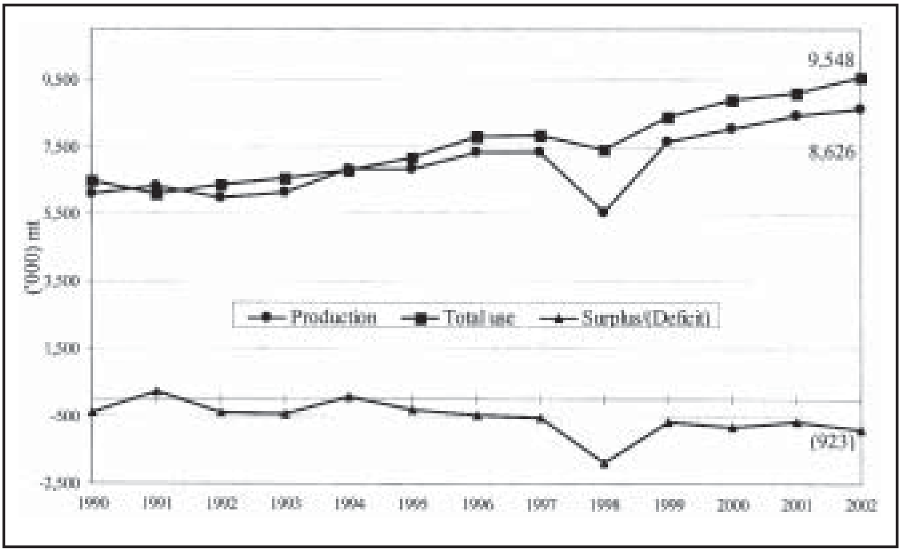

Figure 2. Trends in rice production, utilization, and importation in the Philippines, 1990–2002.

In the Philippines, 65% more rice, relative to present levels, has to be produced by 2025 to keep pace with demand by a projected population of about 107 million, growing by 2.3%/year (Figure 2). To keep up with projected demand, rice-production growth must be sustained at 3%/year, if importation is to be avoided, as espoused by many Asian governments. Given that annual rice-production growth rates have been decelerating to less than 2% per year, and the land frontier—the primary source of growth in recent years—is closing (Table 1), major technological progress has to be achieved in the next two decades for the population demand for rice to be met locally. Against the backdrop of decreasing land, labor, and water that can be devoted to rice production due to increasing competition from non-farming sectors, the challenge to increase rice productivity is indeed enormous.

TABLE 1. SOURCES OF GROWTH OF RICE PRODUCTION IN THE PHILIPPINES, 1970-2001.

Source of growth	All		Wet season		Dry season	
	1970–86	1986–01	1970–86	1986–01	1970–86	1986–01
	(%)					
Area	–0.18	0.96	–1.0	–0.89	1.4	2.9
Yield	3.9	0.67	3.9	0.71	3.5	0.66
Production	3.6	1.6	2.9	–0.18	4.9	3.6

CONSTRAINTS IN ASIAN RICE PRODUCTION

Rice productivity and quality are severely compromised by pests, diseases, and physiological and environmental factors. The crop is the world's single largest market for agrochemicals, consuming around US$3.7 billion annually, with agrochemical costs and crop losses amounting to tens of billions of dollars per year (DFID, 2004). Furthermore, rice cultivation per se is hobbled by resource constraints such as scarcity of water and scarcity of land. Clearly, therefore, technological progress is required in both the biotic and abiotic fronts.

There is a need to increase water productivity of rice.

Scarcity of Water

Rice is a moisture-hungry crop. It consumes twice the water needed to grow corn or wheat. Producing 1 kg of rice requires from 3,000 to 5,000 L of water (Cantrell and Hettel, 2004). In Asia, 90% of the total diverted freshwater is used for irrigated agriculture and, of this, 50% is used to grow rice (IRRI, 2001). By 2025, however, a "physical water scarcity" is expected in Asia's more than 2 million hectares (Mha) of irrigated dry-season rice and 13 Mha of irrigated wet-season rice, and most of Asia's 22 Mha of irrigated dry-season rice will be hampered by "economic water scarcity" (Tuong and Bouman, 2002). As drought is one of the main constraints to high yields also in rainfed-production systems in both the lowlands and the uplands, there is a need to increase water productivity of rice (Cantrell and Hettel, 2004).

Scarcity of Land

Due to competition from non-farming sectors, the land devoted to rice production is decreasing in many Asian countries. In the Philippines, for example, about 10,000 ha of prime rice land is lost annually to the urban and industrial sectors. With water resources becoming limiting and enormous resources required to construct irrigation facilities, there appears to be little room for future expansion of irrigated areas in developing countries. Hence, the contributions of fragile environments such as the rainfed lowlands, uplands, and salinity-prone areas to rice productivity growth will be increasingly important. Technologies, therefore, will be required not only for increasing rice productivity in these environments, but also for preventing resource and environmental degradation in marginal areas.

Pests and Diseases

Intensive and continuous cultivation makes rice vulnerable to various pests and diseases. Although breeding for resistance, coupled with popularizing integrated pest management, has contributed to managing pest populations and minimizing damage levels in many Asian countries, a wide range of viral, bacterial, and fungal diseases still causes economic losses in farmers' fields. For example, tungro, the most destructive viral disease in Southeast Asia, results in crop losses worth more than US$1.8 billion annually (DFID, 2004). On the other hand, aside from causing damage by direct feeding, insect pests also act as vectors for various important rice diseases. Among the most important in the Philippines, are tungro, bacterial leaf blight, sheath blight, and rice blast, while the important insect pests are brown planthopper, whiteback planthopper, and green leafhopper, the latter being the vector for the tungro virus.

Constraints and Yield Loss

Yield losses due to biophysical constraints have been extrapolated for Asia by Hossain (1997) and Evenson *et al.* (1996) (Table 2). In the irrigated ecosystem, yield losses due to technical constraints accounted for 20% (962 kg/ha) of the average yield, with soil-related problems being the most significant. On the other hand, yield losses due to technical constraints accounted for 33% of average yield in rainfed lowland and flood-prone ecosystems, with submergence being the most important, while it was more than 40% of the average yield in the upland ecosystem, with drought being the most significant. Overall, all technical constraints caused a total yield loss of about 23% or 833 kg/ha in Asia, with abiotic factors being more important than biotic for all ecosystems. Climate-related constraints like submergence, drought, and cold resulted in yield losses that ranged from 227 kg/ha (20% of average yield) for upland to 429 kg/ha (28% of average yield) for flood-prone ecosystems. Yield losses due to pests and diseases, on the other hand, were most significant in the rainfed ecosystem while those due to weeds were most important for the upland environment.

Tropical Hybrid Rice

In addition to China, a number of countries in tropical Asia, notably, India, Vietnam, the Philippines, Indonesia, Bangladesh, and Sri Lanka have launched national programs aimed at commercializing hybrid rice. These programs aim to exploit the phenomenon of heterosis or hybrid vigor, which provides about 1 to 1.5 t/ha (15 to 20%), higher yields than those obtained using the best inbred varieties under irrigated conditions. The associated seed-production technology that must accompany commercialization promotes the development of seed industries that provide additional rural employment. Already a commercial success in China,

TABLE 2. YIELD LOSS DUE TO TECHNICAL CONSTRAINTS IN THE RICE ECOSYSTEMS OF ASIA (EVENSON *ET AL.*, 1996).

Constraint	Irrigated	Rainfed lowland	Flood-prone	Upland	Average loss for Asia	
			(kg/ha)			(%)
Biotic						
Diseases	69	146	18	70	83	3.1
Insects	108	166	16	65	110	2.3
Other pests	29	88	21	120	52	1.4
Abiotic						
Water	400	288	429	227	358	9.9
Soil	356	75	13	80	229	6.4
Total	962	763	496	563	833	23
Loss of yield (%)	20	33	33	40	23	

In the Philippines, the commercialization of hybrid-rice technology has been embraced as the government's banner program for agriculture.

where 15 Mha (50% of the total rice area) are planted to hybrid rice varieties, about 1 Mha were estimated to be planted to hybrids in tropical Asia in 2003 (Virmani, 2003). In the Philippines, the commercialization of hybrid-rice technology has been embraced as the government's banner program for agriculture, with 200,000 ha planted to seven commercially released hybrids in 2004 (Redoña *et al.*, 2003). Results of the program from 2001 to 2003 showed an average superiority in the yield of hybrids of 1.59 t/ha or 36% over that of modern inbred varieties.

New Plant Type

In the early 1990s, IRRI started developing "new plant type" (NPT) rice that is expected to reach farmers' fields during this decade. With redesigned plant architecture that increases total biomass and harvest index, these "super" varieties—intended for direct seeding—are expected to yield about 20% more than current modern varieties. Several NPT lines with yields >10 t/ha have already been distributed, *e.g.* to Indonesia and the Philippines, for adaptation trials and three NPT varieties have already outyielded popular modern varieties in China by more than 1 t/ha (Cantrell and Hettel, 2004). NPT rices trace their lineage to both the indica and japonica subspecies and are, therefore, also valuable sources of genetic diversity in breeding for higher yield potential and heterosis.

"Aerobic" Rice

To strategically address the projected water scarcity, IRRI has also developed an "aerobic rice" technology that aims to significantly reduce the crop's water requirement below current levels. Patterned after the rice grown in irrigated upland areas of Brazil, the "aerobic" plant for tropical Asia is expected to yield 6 to 7 t/ha under a crop-management system that will provide only half as much water as rice requires today (Cantrell and Hettel, 2004). In China, where "aerobic" rice has been tested on 190,000 ha, yields of 6 to 7 t/ha have been obtained, while, in the Philippines, several varieties with yield potentials of approximately 6 t/ha have been identified for use under "aerobic" conditions (Bouman, 2003).

Integrated Crop Management

Following the successful promotion of an integrated pest management program across Asia, an even more comprehensive rice-crop management system—designed to close the yield gap—is being piloted in Vietnam, Thailand, Indonesia, and the Philippines, with the support of the United Nations Food and Agriculture Organization (FAO). It is referred to as "rice integrated crop management" (RICM). Similar to the Rice Check system that has been dubbed a major contributor to increases in rice yields in Australia, from 6 t/ha in 1987 to 9.7 t/ha in 2000 (Nguyen, 2002), it provides a platform for the integration of different production technologies and decision-making support tools that should allow farmers to move closer to the practice of real-time precision rice agriculture. In the Philippines, a Rice Check prototype that involves eight key checks throughout the growing season was piloted on-farm beginning in 2004.

Rice-Based Farming Systems

In line with the Asia's aim to improve the profitability of rice farming, alleviate poverty, and achieve food security at the household level, particularly in marginal or fragile environments where the poorest of Asia's farmers live, diversified systems that integrate crop, livestock, and fish components are being developed in several countries. In the Philippines, for example, crop relays that result in the highest profits have been identified for the rainfed lowland ecosystem, planting calendars based on agroclimatic data have been formulated for adoption by farmers, and GIS suitability maps have also been developed for use of local government units in the prioritization of agricultural programs.

Beginnings of Biotechnology in Rice

In modern parlance, "biotechnology" generally refers to genetic manipulation at the DNA level. However, it is important to note that not all biotechnology involves genetic engineering or recombinant DNA techniques that result in transgenic plants or genetically modified (GM) organisms. In the strictest sense, biotechnology could also refer to specialized fermentation processes, *in-vitro* culture techniques such as embryo rescue and double haploidization, and protein engineering. For the purpose of this paper, however, "biotechnology" will imply manipulations at the level of DNA.

The potential of plant biotechnology to contribute greatly to the world's fight against hunger and malnutrition, poverty, and environmental degradation—despite claims to the contrary—has already been generally acknowledged. In Asia, agricultural biotechnology has been recognized as having the potential to:

- increase crop and animal productivity,
- improve nutritional quality of food,
- broaden tolerance of crops for drought, salinity, and other abiotic stresses, and
- increase resistance of crops to pests and diseases (ADB, 2001).

Applied to problems of poor farmers, biotechnology holds the greatest promise for increasing yield potential and quality in many crops. This in turn should enhance the attainment of sustainable household and national food security and proper human nutrition, while increasing profits and reducing farming costs, thereby contributing to poverty alleviation, especially in fragile environments, where most of Asia's poor live.

One of the most comprehensive assessments of the potential that biotechnology holds for a given crop was made for rice by the Rockefeller Foundation (RF) in the process of developing its International Program on Rice Biotechnology (IPRB) (O'Toole *et al.*, 2001). Culminating in the publication Rice Research in Asia: Progress and Priorities (Evenson *et al.*, 1996), a series of studies identified the top-twenty priority traits for biotechnology research intervention, balancing research costs *vis-à-vis* the benefits from expected increases in rice productivity or value (Table 3). With clear research priorities in place, in the mid-1980s RF supported a 17-year program that laid the scientific foundation for rice biotechnology as we know it today. At about the same time, national agricultural research systems (NARS) around Asia began building capacity for biotechnology. The salient accomplishments of the IPRB include:

- the generation of the first DNA molecular marker map of rice;
- the transformation and regeneration of rice;
- the use of rice-pest genomic information to understand host-plant resistance;
- discoveries that changed the way rice geneticists view breeding objectives, such as insect resistance, abiotic-stress tolerance, and hybrid rice;
- the discovery of rice's pivotal genomic position in the evolution of cereal species;
- the transfer of resulting biotechnologies to institutions in rice-producing and -consuming countries; and
- the strengthening of both physical and human resources in cooperation with national and international rice research systems in Asia, Africa, and Latin America (O' Toole *et al.*, 2001).

TABLE 3. IMPORTANCE OF RICE RESEARCH CHALLENGES MEASURED BY EQUITY-WEIGHTED NET PRESENT VALUE (NPV) AND POTENTIAL OF BIOTECHNOLOGY (BT) TO ADDRESS THE CHALLENGE (HERDT, 1991).

Challenge	NPV worldwide	Weighted NPV x BT potential
Brown planthopper	1,944	1,944
Tungro virus	1,726	6,905
Gall midge	1,292	2,583
Greater lodging resistance	1,228	1,228
Cytoplasmic male sterility	1,161	2,322
Upland drought/blast	1,085	1,962
Yellow stem borer	945	3,781
Submergence (flash flood)	842	1,685
Weeds	718	359
Seedling vigor	540	1,080
Birds	412	206
Cold at seedling	310	310
Drought at anthesis	288	575
Apomixis	275	275
Bacterial blight	274	137
Waterlogged	262	524
Coastal saline/acid	256	256
Sheath blight	168	336
Storage insects	158	158
Ragged stunt virus	155	621

More than 400 rice scientists, primarily from Asia, were trained in advanced laboratories around the world.

The last item involved international collaborative research-cum-training that successfully linked emerging national rice biotechnology efforts directly to advanced research institutes in the United States, Europe, Japan, and Australia, resulting in the training of more than 400 rice scientists, primarily from Asia, in advanced laboratories around the world. At least seventy-three institutions in twelve Asian countries have received research grants and had up to twenty scientists funded for formal training, including: PhD fellowships; dissertation fellowships; postdoctoral fellowships; visiting-scientist fellowships; biotechnology career fellowships; and technology-transfer fellowships in advanced laboratories and universities in developed countries (Table 4, O'Toole *et al.*, 2001).

TABLE 4. BREAKDOWN OF NUMBER OF INSTITUTIONS BY COUNTRY WHERE FORMAL TRAINING WAS SPONSORED UNDER THE ROCKEFELLER FOUNDATION'S INTERNATIONAL PROGRAM ON RICE BIOTECHNOLOGY (O'TOOLE *ET AL.*, 2001).

	Number of institutions according to number of researchers trained[a]						
Country	>20	15–19	10–14	5–9	3–4	1–2	0
Bangladesh	–	–	–	1	1	–	–
China	–	1	4	4	2	6	5
India	1	1	–	5	7	7	3
Indonesia	–	–	–	1	–	1	–
Malaysia	–	–	–	–	–	1	–
Nepal	–	–	–	1	–	–	2
Pakistan	–	–	–	1	–	–	1
Philippines	–	–	1	1	–	–	
South Korea	–	–	1	–	–	–	1
Sri Lanka	–	–	–	–	–	–	1
Thailand	–	–	1	1	–	3	1
Vietnam	–	–	1	2	–	3	–
Latin America	–	–	–	–	–	1	3
Total	1	2	8	17	10	22	17

[a]Column headings reflect the number of scientists trained under IPRB sponsorship.

The Asian Rice Biotechnology Network (ARBN) was formed in 1993, with IRRI as coordinator. It facilitated collaborative research amongst several Asian rice-breeding programs with a primary objective of developing disease-resistant varieties through the application of DNA-marker technology (Leung *et al.*, 2004). Among the major Asian R&D institutions involved were the Indonesian Agricultural Biotechnology and Genetic Resources Institute in Bogor, Indonesia; the Central Rice Research Institute in Cuttack, Orissa, India; the Punjab Agricultural University in Ludhiana, Punjab, India; the Philippine Rice Research Institute (PhilRice) in Muñoz, Nueva Ecija, Philippines; the Agricultural Genetics Institute in Hanoi, Vietnam; and the China National Rice Research Institute (CNRRI) in Hangzhou, Zhejiang, China.

Progress in Rice Biotechnology Applications

With increased activities in biotechnology from the mid-1980s, rice gradually became the "model monocot" in molecular genomics research, and eventually was the first food crop to have its genome sequenced. Among the key advantages that rice offered as a model system were its small genome (~430 Mb) (Arumuganathan and Earle, 1991); the development and availability of a complete genome sequence (Komari *et al.*, 1998; Feng *et al.*, 2002; Goff *et al.*, 2002; Sasaki *et al.*, 2002; Yu *et al.*, 2002; The Rice Chromosome 10 Sequencing Consortium, 2003), its diverse germplasm (84,000 accessions at IRRI); and the development of a number of key resources for genomic mapping research (Chen *et al.*, 2002; McCouch *et al.*, 2002; Wu *et al.*, 2002). The progress achieved in biotechnology applications for rice improvement in two major areas—the use of molecular markers for identifying and introgressing favorable genes and gene combinations within the rice species, and the use of transgenic technologies to incorporate traits for herbicide tolerance, biotic-stress resistance, abiotic-stress resistance, and nutritional value into rice—was recently summarized by Coffman *et al.* (2004).

Use of Molecular Markers

The development of the first rice molecular map in the late 1980s (McCouch *et al.*, 1988) sped up molecular genetics research in rice. Among the early molecular marker applications for rice improvement were:

- construction of dense genetic maps using different populations,
- tagging and/or introgression of major genes and those underlying quantitative traits, referred to as quantitative trait loci (QTL),
- high-resolution characterization and fingerprinting of germplasm,
- assessment of the diversity of germplasm pools, and
- map-based gene cloning.

Molecular markers offered great potential for increasing the precision and speed of rice breeding as, among other advantages over phenotypic markers, they provided the ability to screen breeding populations regardless of growth stage; they permitted screening for traits that were extremely difficult, expensive, or time consuming to score phenotypically; and they distinguished the heterozygous condition without need for progeny testing (Coffman *et al.*, 2004). Molecular markers provided geneticists with powerful tools to dissect the inheritance of economically important traits, many of which are quantitatively inherited and complex in nature. Thus, studies dealing with QTLs were carried out on seedling vigor and tolerance to a variety of environmental stresses including drought, submergence, salinity, and mineral deficiencies and toxicities (Champoux *et al.*, 1995; Redoña and Mackill, 1996; Xu and Mackill, 1996; Flowers *et al.*, 2000; Gregorio, 2002; Price *et al.*, 2002). These traits were considered primary targets for molecular marker-aided selection (MAS) as breeding for them using conventional techniques often proved to be difficult.

MAS, or the selection of traits based on the presence or absence of a molecular marker (in *lieu* of phenotype) has already received a lot of emphasis in rice. The development of simple and less-costly marker systems based on the polymerase chain reaction (PCR) such as the simple sequence repeats or SSRs (McCouch *et al.*, 2002) contributed greatly to the use of MAS in various laboratories in developing countries. For example, at PhilRice—the NARS for rice in the Philippines—MAS studies are conducted to develop varieties resistant to bacterial blight, including the pyramiding of two to three bacterial-blight-resistance genes in a common genetic background, both for inbred and hybrid rice breeding. Gene pyramiding is expected to provide durable resistance against insect pests and diseases; early attempts in this direction were focused on bacterial blight and rice blast diseases and the brown planthopper. Introgressing genes from wild relatives into cultivated rice has also been accomplished with the aid of molecular markers, such as the bacterial-blight-resistance gene from *Oryza longistaminata* (Ronald *et al.*, 1992), and the yield traits from *O. rufipogon* (Thomson *et al.*, 2003). Markers have also been used to minimize the linkage drag that occurs in wide crosses and to obtain the desired recombinants in fewer generations during backcrossing (Blair *et al.*, 2003; Takeuchi *et al.*, 2003). Whole-genome, marker-based selection fosters new opportunities and makes efficient use of genetic variation both in cultivated rice and its wild relatives.

One of the most significant developments aided by the use of molecular markers in rice was the map-based cloning of Xa 21 and its subsequent use in developing varieties with broad-spectrum resistance to bacterial blight (O'Toole *et al.*, 2001). Starting with the genetic mapping, using RFLP markers of the Xa 21 locus in 1990 (Ronald *et al.*, 1992), the gene was cloned using map-based cloning techniques and a bacterial artificial chromosome library was made by 1995 (Song *et al.*, 1995; Wang *et al.*, 1995). By 1997, the gene had been pyramided with other Xa genes using PCR-based MAS (Huang *et al.*, 1997) and, by 1998, Xa 21 had been transformed into elite lines (Zhang *et al.*, 1998); field trials were conducted in China, India, and the Philippines by 1999. By 2000, a hybrid rice parental restorer line had been improved through MAS, resulting in resistant hybrid rices under field conditions (Chen *et al.*, 2000).

The IRRI-coordinated ARBN, supported by the Asian Development Bank (ADB) and the RF, played a key role in developing capacity for marker-aided analyses of pathogens and host-plant resistance in several national breeding programs. This network approach was found essential for the sharing of resources and providing sustained training in the adoption of new biotechnology tools and genetic knowledge in individual breeding programs of various NARS in Asia (Leung *et al.*, 2004). As a result of ARBN activities, elite or commercial rice lines with multiple disease-resistance genes have been developed in several participating countries (Table 5).

Table 5. Marker aided selection-improved varieties and their corresponding increases in yield developed by research teams from Asian NARS (Leung *et al.*, 2004)

Country	Background commercial/ Yield standard	Released (R)/ Near-release(NR)	Yield (t/ha)	Gain over yield standard (%)
Philippines	IR64	AR32-19-3-2 (NR)	5.1	0
	IR64	AR32-19-3-3 (NR)	6.7	31.4
	IR64	AR32-19-3-4 (NR)	6.1	19.6
	BPI Ri10	AR32-4-3-1 (NR)	6.0	17.6
	BPI Ri10	AR32-4-58-2 (NR)	6.5	27.5
	PSB Rc28	Yield standard	5.1	–
Indonesia	IR64	Angke (Bio-1) (R)	5.4	20.0
	IR64	Conde (Bio-2) (R)	5.4	20.0
	IR64	Yield standard	4.5	–
India	PR106	IET17948 (PR106-P2) (NR)	8.2	22.4
	PR106	IET17949 (PR106-P9) (NR)	7.9	17.9
	PR106	Yield standard	6.7	–
China	Zhong 9A/ Zhonghui 218	Hybrid Guofeng No. 2 (NR, R)	7.8	11.4
	II-3A/ Zhonghui 218	Hybrid II You 218 (NR, R)	8.3	18.6
	Shanyou 46	Yield standard	7.0	–

No transgenic rice has yet been commercialized in an Asian country. However, two GM varieties, both with herbicide tolerance, have passed the regulatory approval processes in the United States: the Liberty-Link™ rice of Aventis Crop Science (now Bayer CropScience) and CLEARFIELD™ rice from BASF, Inc.

Use of Transgenic Technologies

No transgenic rice has yet been commercialized in an Asian country. However, two GM varieties, both with herbicide tolerance, have passed the regulatory approval processes in the United States: the Liberty-Link™ rice of Aventis Crop Science (now Bayer CropScience) involving phosphinothricin (PPT) herbicide tolerance, specifically ammonium glufosinate, and CLEARFIELD™ rice involving imidazolinone herbicide tolerance from BASF, Inc. (AgBios, 2004). Ten trials on 11 ha and twelve trials on 45 ha were conducted in 2002 and early 2004, respectively, 90% of which involved Monsanto (Jia *et al.*, 2004). To indirectly gauge the extent of use of GM technology Coffman *et al.* (2004) utilized information on patent applications and classified these into the areas of:

- herbicide tolerance,
- biotic-stress resistance,
- abiotic-stress resistance; and
- nutritional traits.

Up to 2002, 307 patents had been filed in rice biotechnology from 404 different groups (Brookes and Barfoot, 2003). The largest number of patents was held by DuPont/Pioneer (sixty-eight), followed by Monsanto (thirty-three), Syngenta (thirty-two), Bayer (nineteen), public sector institutions in Japan, and Japan Tobacco.

***For abiotic-stress tolerance, transgenic rice plants that produce trehalose at three to ten times the normal rate—resulting in tolerance to drought and/or salinity—have been developed by introducing the otsA and otsB genes for trehalose biosynthesis from* Escherichia coli.**

Amongst various traits, herbicide tolerance has been the major focus for the private sector. In the United States, Monsanto and Bayer were responsible for 80% of GM-rice field trials, primarily addressing herbicide tolerance (Brookes and Barfoot, 2003). Other countries in which herbicide-tolerant GM rice has been field tested include Italy, Brazil, Argentina, and Japan, and possibly China (Coffman *et al.*, 2004). Biotic-stress resistance, on the other hand, has been the primary focus for public-sector research institutions including those in Asia (Brookes and Barfoot, 2003). Specific traits being worked on using GM technologies include resistance to bacterial blight using the Xa21 gene, rice blast, rice hoja blanca virus, rice tungro spherical virus, rice yellow mottle virus, rice ragged stunt virus, the brown planthopper, and yellow stem borer, the latter—using *Bt* technology—being the closest to commercialization. For abiotic-stress tolerance, transgenic rice plants that produce trehalose at three to ten times the normal rate—resulting in tolerance to drought and/or salinity—have been developed by introducing the otsA and otsB genes for trehalose biosynthesis from *Escherichia coli* (Garg *et al.*, 2002).

Perhaps one of the most promising, albeit controversial, applications of transgenic technology in rice has been the development of vitamin A-enriched varieties, popularly known as Golden Rice™ due to the slightly yellow color conferred to the endosperm (Potrykus, 2000; Figure 3). Beginning as a collaborative project in the early 1990s between the Swiss Federal Institute of Technology (ETH-Zurich) and the University of Freiburg, Germany, with Ingo Potrykus and Peter Byer, respectively, as lead collaborators, the Golden Rice™ project drew financial support from ETH-Zurich, the European Commission, and the Rockefeller Foundation.

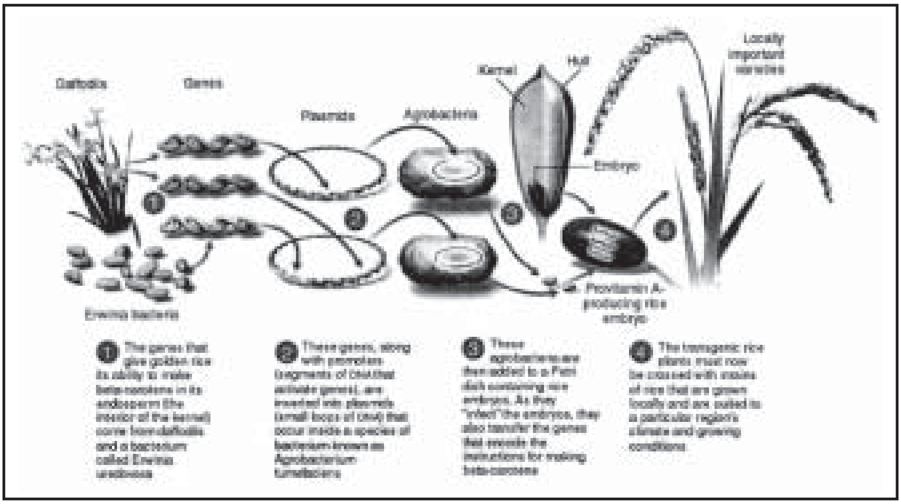

Figure 3. Development of Golden Rice™ (ISAAA, 2004a).

Vitamin A is considered essential for children and women of childbearing age and, worldwide, nearly 134 million children are at risk for diseases related to vitamin-A deficiency (VAD), including some 3.1 million preschoolers who suffer from eye damage, and nearly 2 million under 5 years of age who die each year from diseases linked to persistent VAD. In Southeast Asia alone, 5 million children become at least partially blind every year due to VAD. Golden Rice™ has the potential to improve the supply of vitamin A in the human diet, thereby, alleviating the suffering and death of millions of people, especially those who cannot afford diet diversification (ISAAA, 2004a).

With the proof of concept for rice to produce and accumulate pro-vitamin A (beta-carotene) in the seed endosperm tissue through genetic engineering already demonstrated (Beyer *et al.*, 2002), new vitamin-A enriched materials are now in the pipeline, including several popular Asian indica varieties such as IR64. Some of these new materials are said to contain ten times more pro-vitamin A than the original Golden Rice™ material that was eventually found unsuitable for commercialization as they were in a genetic background (japonica) not grown in most Asian countries. Reported to involve "clean" events, without cross-border transfers or antibiotic markers, the new materials are being readied for backcrossing and stability and field testing in 2004, while vitamin-A absorption and bioavailability tests are underway or planned in the Philippines, China, and the United States (Datta *et al.*, 2003; Coffman *et al.*, 2004; Cantrell and Hettel, 2004).

Another promising use of transgenic technology to improve human nutrition is in combating iron deficiency. One of the most common micronutrient deficiencies, it affects about 3.5 billion people worldwide and causes anemia, heart problems, neurological disorders, *etc.* The ferritin gene from *Phaseolus vulgaris* has been introduced into rice, resulting in doubling to tripling of the iron content in the endosperm, even after polishing the grain (Vasconcelos *et al.*, 2003). To improve the bioavailability of iron, since it is usually complexed with phytic acid, genes from *Aspergillus fumigatus* encoding a thermotolerant phytase protein and a cysteine-rich metallothionein-like protein were also introduced into rice resulting in a seven-fold increase in cysteine level and a 130-fold increase in phytase level (ISAAA, 2004b).

Only the Philippines has so far approved the commercial release of a transgenic food crop: a **Bt*****-enhanced corn.***

Many NARS in rice-growing countries of Asia that are endowed with universities and agricultural research institutes with biotechnology research capacity are actively involved in research on transgenic technologies, encouraged by supportive government policies. In a recent study by the International Food Policy Research Institute (Atanassov *et al.*, 2004), 209 transformation events were reported to have already been done in seventy-six scientific institutes in sixteen countries. Of these, 109 (52%) were done in seven Asian countries, namely, China (thirty), Indonesia (twenty-four), India (twenty-one), Philippines (seventeen), Thailand (seven), Pakistan (five), and Malaysia (five). Of these countries, however, only the Philippines has so far approved the commercial release of a transgenic food crop: a *Bt*-enhanced corn. Although the highest number of transformation events for any crop was reported for rice (18%), followed by potato (11%), maize (8.6%), and papaya (6.2%), a GM rice variety has yet to be commercialized in Asia.

To hasten public acceptance of biotechnology, a massive public-education campaign uses the tri-media as well as various public fora, and involves the government, private, NGO, and religious sectors.

In the Philippines, both IRRI and PhilRice have on-going biotechnology programs employing molecular marker and transgenic technologies, as well as other more conventional techniques such as *in-vitro* culture and wide hybridization. With the Philippine government declaring a supportive policy, the use of biotechnology is embedded as a strategy for achieving the goals set by the irrigated lowland, direct-seeded, rice for fragile environments, and hybrid rice multidisciplinary R&D programs of PhilRice. GM technology, in particular, is being used to improve high-yielding varieties, including NPTs and hybrid parental lines (Aldemita *et al.*, 2004). The Philippine focus is on tungro, sheath blight, blast, and bacterial blight diseases, as well as on insect stem-borer, and tolerance of salinity. Genes procured from laboratories around the world and modified for *Agrobacterium tumefaciens*-mediated transformation, are being used to generate transgenic plants. A number containing chitinase and glucanase genes have already been produced and tested under controlled screenhouse conditions. Moreover, PhilRice has conducted the first and only contained field trials for any GM rice in the Philippines; transgenic IR72 plants containing the Xa21 gene for bacterial-blight resistance showed complete resistance to nine Philippine races of the pathogen. Furthermore, transgenic plants with the pin2 gene are being developed to improve stem-borer resistance, while a coat-protein gene from the rice tungro bacilliform virus is being used in *A. tumefaciens*-mediated transformation. PhilRice, a member of the Golden Rice™ Network, has undertaken backcrossing work on discarded original Golden Rice™ materials. To expedite the availability of vitamin-A enriched rice to consumers, PhilRice hopes to continue its active participation in this network, which involves other Asian countries such as Indonesia, Vietnam, India, Bangladesh, and China, as well as partners in developed countries such as the United States, Germany, the United Kingdom, and Switzerland. Already, guidelines on the national testing of GM rice prior to commercialization are being prepared. To hasten public acceptance of biotechnology in general, and GM rice in particular, PhilRice, along with other Philippine government agencies, has spearheaded a massive public-education campaign using the tri-media as well as various public fora, and involving the government, private, NGO, and religious sectors.

Work in Progress

The availability of the complete rice-genome sequence offers opportunities to further our understanding of natural genetic variation and the effects of alleles and their interactions, particularly for traits that are of importance in rice breeding, using specific genetic backgrounds and under specific environments. At IRRI, for example, biotechnologists are systematically assessing the array of phenotypes resulting from the disruption of putative gene sequences in mutants, near-isogenic lines, permanent mapping populations, and elite and conserved germplasm through an initiative on functional genomics (Hossain *et al.*, 1997; Leung *et al.*, 2004). However, these gene-discovery and allele-mining efforts require the annotation of the rice genome and the subsequent construction of databases and information resources. The use of information and communication technology and bio-informatics, such as the IRIS (Bruskiewich *et al.*, 2003; http://www.icis.cgiar.org/) and GeneFlow (http://www.geneflow.com) databases, should make the accumulating information more easily accessible to scientists, especially breeders in rice-growing countries.

Other work in progress includes attempts to transfer the C_4-photosynthetic pathway and leaf anatomy genes of maize to C_3 rice in order to improve the latter's radiation-use efficiency while reducing transpirational water loss and N-fertilizer requirement, and studies aiming to more thoroughly understand genetic variation for drought tolerance using genomics and bioinformatics tools in order to identify the exact genes involved (Cantrell and Hettel, 2004). Another promising area is the genetic engineering of N_2-fixation capacity into rice; attempts to engineer the nif-regulon into the chloroplast genome have the objective of making rice only partially dependent on external N and able to provide additional N during the grain-filling period to maintain the photosynthetic apparatus for a longer period of time (Potrykus, 2000). Over the medium and long terms, apomixis research, started earlier at IRRI, needs to be vigorously pursued using biotechnology in order to capture—and make available to resource-poor farmers—the benefits of heterosis.

Issues, Concerns, and Opportunities

Setting Biotechnology R&D Priorities

It may be argued that most of the earlier rice biotechnology activities, particularly in the public sector, and on transgenic technology applications, were more science-driven than attuned to the needs of ordinary farmers. A case in point is the development of Xa 21-enhanced IR72, a variety that, while high-yielding, is of little economic importance to farmers. In this regard, it is important to note that for GM rices to be useful, at least in the short term, and to gain rapid acceptance amongst resource-poor farmers, it is best that they be derived from varieties already widely grown and suited to specific agroenvironments (DFID, 2004). Ranged against the challenges confronting rice cultivation in most Asian rice-growing countries today, it is clear that, trait-wise, to have the greatest impact, international as well as NARS biotechnology research should focus, on one hand on the most important diseases and pests, and physiological and environmental factors that reduce productivity and quality as discussed earlier, and on the other hand on increasing yield potential. An example of trait prioritization, has been advanced by Hossain *et al.* (1997, Table 6) for achieving the greatest impact on the lives of poor rice farmers and consumers, while being complementary to conventional rice-improvement efforts. Obvious from their analysis is the treatment of biotechnology not as a be-all solution to existing problems but as a tool or strategy complementary to conventional breeding efforts. To ensure relevancy of the biotechnology R&D agenda, a bottom-up approach is needed in the crafting of priorities, with farmers' and other stakeholders' needs and concerns adequately addressed. Such an approach should benefit from the rich indigenous knowledge of local farming communities on specific rice-production constraints, while facilitating public acceptance and ensuring the "trickling down" of benefits from biotechnology-derived products.

It is incumbent upon the public sector to develop a "pro-poor" biotechnology R&D agenda.

Need for More Public Investments

There remains an imbalance in R&D investments in rice biotechnology that tends to favor developed countries, thus impacting on the potential of biotechnology to boost agriculture in the developing world and to alleviate the plight of resource-poor rice farmers. The concentration of biotechnology R&D in developed countries and the limited private-sector effort in developing countries, particularly in Asia, has raised concerns over the economic concentration of biotechnology in favor of developed countries and multinational companies (ADB, 2001). As the private sector is unlikely to undertake rice biotechnology research based primarily on the pressing needs of resource-poor farmers—due to difficulties in recouping costly investments—it is incumbent upon the public sector to develop a "pro-poor" biotechnology R&D agenda. Furthermore, public research products would have to gain similar approval as those developed by the private sector if transgenic research products and their concomitant potential benefits are to reach the poor.

While scientists in Asian countries have demonstrated the capacity to successfully undertake biotechnology R&D relevant to the needs of resource-poor farmers, the desired phenotypes have been few when compared to traits being developed by multinational firms and advanced research institutes in the developed world (Nuffield Council on Bioethics, 2004). One noteworthy aspect, however, has been the case of Thailand, which established the National Center for Genetic Engineering and Biotechnology (BIOTEC) in 1983. BIOTEC has supported biotechnology R&D in six areas, including the improvement of disease resistance in rice, particularly against rice blast. This disease affected 200,000 ha of rice in Thailand in 1993, causing serious economic loss and resulting in government intervention to

Table 6. Prioritization of traits for biotechnology intervention in different rice-growing environments (Hossain *et al.*, 1997).

Priority traits		Target environment	Available products	Preferred approaches*: Conventional breeding	Marker-aided selection	Transgenic
Stress tolerance	Bacterial blight	Rainfed lowland	Genes, markers, transgenic lines	++*	++++	++++
	Sheath blight	Irrigated, high yield	Transgenic lines	+	+	++++
	Blast	Upland	Markers	+++	+++	+
	Stemborer	All	Transgenic lines	+	0	++++
	Drought	Rainfed lowland, upland	Under development	++	+	+
	Salinity	Coastal		+++	+	++
Nutritional value	Vitamin A	areas	Gene constructs, transgenic lines	+	0	++++
	Fe		Gene constructs	+++	0	+++
	Zn			+	0	?
Yield enhancement		All ecosystem	Elite lines	++++	++	++

*The more "+" marks, the higher the priority; 0 = not applicable.

With field testing of various transgenic rices in progress since 1998, and with 53 ha planted in 2003, China is poised to becoming the first country in the world to commercialize transgenic rice.

assist stricken farmers, costing about US$10 million. Since then, BIOTEC has supported research for the molecular genetic characterization of local blast isolates and mapping of blast-resistance genes, with focus on aromatic varieties for Thailand's export rice market. In 1999, BIOTEC also provided US$3.7 million to fund the "Rice Genome Project Thailand," particularly for the sequencing of rice chromosome 9, which contains a QTL for tolerance of submergence, a very important concern of Thai farmers (Tanticharoen, 1997). Most rice-growing countries in Asia, with the exception of China and India (Atanassov *et al.*, 2004), however, have yet to launch similarly focused government initiatives on rice biotechnology R&D. In China, investments on public-sector biotechnology research have risen dramatically to $1.2 billion for 2001–2005, a 400% increase over 1996–2000 levels, with about $120 million allocated for transgenic rice R&D (Jia *et al.*, 2004). With field testing of various transgenic rices in progress since 1998, and with 53 ha planted in 2003, China is poised to becoming the first country in the world to commercialize transgenic rice.

Importance of Collaboration

Given the varying capacities for biotechnology research among rice-growing NARS and the limited resources allocated for biotechnology research in the public sector—unintentionally abetted by the phasing out of the Rockefeller Foundation's IPRB (O'Toole *et al.*, 2001), the constraints in NARS R&D budgetary allocations, and the reduction of funding support for international agricultural research centers (IARCs) including IRRI (Cantrell and Hettel, 2004), the need for biotechnology R&D practitioners to collaborate has become paramount. Collaborations need to be pursued at the individual, institutional, governmental, bilateral, regional, and international levels to ensure not only that the highest returns for R&D investments are attained, but also to facilitate regulatory approvals and biotechnology product commercialization. At the national level, the creation of a coordinating body such as BIOTEC in Thailand (Tanticharoen, 1997) should provide a mechanism for increasing efficiency in the use of limited national R&D budgetary allocations through the avoidance of research duplication and through sharing of in-country research capacity. On the other hand, a regional collaboration approach, as exemplified by the ARBN (Leung *et al.*, 2004), should be able to develop a biotechnology R&D agenda focused on the shared needs of rice farmers in the region and, where possible, pool human, scientific, and financial resources or, alternatively, parcel out the research portfolio as was done in the rice-genome-sequencing initiative. One type of formal collaboration that is yet to be explored involves bilateral arrangements between countries. In the development of transgenic technologies, such South-to-South collaboration would facilitate learning and sharing of common approaches, genes, germplasm, regulatory trials, and biosafety-related information (Atanassov *et al.*, 2004). Already established broad-based regional cooperative efforts, such as the Association of Southeast Asian Nations (ASEAN) and the Asia Pacific Economic Conference (APEC) should be tapped to support these regional biotechnology undertakings. At the international level, programs that help rice scientists from developing countries to train, further hone their capacities, and maintain ties with advanced laboratories at the IARCs and in developed countries need to be supported.

IARCs and the Private Sector

With many NARS still not fully able to undertake, solely by themselves, activities spanning the whole biotechnology research, development, and commercialization spectrum, IRRI and similar international institutions will continue to contribute as technology and knowledge providers, as well as builders and enhancers of biotechnology capacity. Of particular importance for IRRI is the provision of strategic research outputs that, already, several NARS in Asian countries are capable of transforming into applications and products. These include protocols, gene constructs, and markers for traits relevant to local problems, but prohibitively expensive for NARS to develop single-handedly. Alternatively, IRRI should be able to complement its strategic research program with a product-development thrust, focusing on biotechnology-derived advanced breeding lines and varieties, with traits commonly of high relevance amongst Asian countries. The product-development portfolio includes varieties that are tolerant of drought, of high nutritional value, and are resistant to major diseases such as tungro and bacterial blight. The role of IRRI as facilitator in the transfer of useful technology and products amongst NARS through the sharing of hardware, knowledge, and experience needs to be strengthened. Equally important is its role in facilitating the formation of effective NARS/public-sector and private-sector collaborations, so that NARS may access private-sector-held intellectual property (IP) on rice biotechnology and products. IRRI can also serve as a clearinghouse for IP-protected technologies from both the public and private sectors to facilitate access by NARS scientists. Training support by IRRI and similar institutions for NARS should now include those designed to advance NARS capacity on the science and management of biotechnology, IP rights, biosafety and food-safety regulations, and international negotiations. As Cantrell and Hettel (2004) argued, with IRRI's strengths, it can serve as the unbiased broker and facilitator amongst the rice NARS, advanced research institutions, and the private sector.

Other international organizations, such as the FAO, can help expedite progress in rice biotechnology in Asia by promoting and supporting networking mechanisms such as the South-to-South cooperation model. They can also help in developing and supporting infrastructure for public-good agricultural research, providing knowledge and training to NARS researchers, enabling interactions amongst stakeholders through dialogue and similar fora, facilitating access to relevant IP, sensitizing policymakers on biotechnology-related issues, and assisting governments in the crafting of biotechnology-related policies. As the primary source of GM crops continues to be the private sector, technology transfer between the private and public sectors—in terms of products as well as experience in regulation, commercial development, and release of GM crops—would greatly benefit NARS. This technology transfer could be facilitated by private foundations such as the International Service for the Acquisition of Agri-Biotech Applications (ISAAA).

In total, seventy intellectual and technical property rights belonging to thirty-two companies and universities were used in product development and for which "freedom-to-operate" situations had to be applied for in order for NARS to begin using Golden Rice™ in further breeding and in de-novo transformation activities using locally adapted varieties

---

Intellectual Property Rights

The impact of IP rights on biotechnology research is often imbedded in discussions on public- and private-sector partnerships. There is a need to balance the fact that, on one hand public-sector institutions, due to limited resources, cannot fully avoid accessing private-sector-held IP during the development of their own products and, on the other hand, the private sector has to avail itself of IP rights protection to be able to safeguard its investments and commercial interests and to enable sharing of its IP with other sectors without fear of exploitation. The development of Golden Rice™ is a case in point. In total, seventy IP rights and technical property (TP) rights belonging to thirty-two companies and universities were used in product development and for which "freedom-to-operate" situations had to be applied for in order for NARS to begin using Golden Rice™ in further breeding and in *de-novo* transformation activities using locally adapted varieties (Potrykus, 2000). Several modalities, however, are still open to the public sector, providing access to genes and technologies from the private sector. These include licensing, the fact that patents have time limits, confidentiality agreements, and the purchase of genes for incorporation into local germplasm. New types of IP agreements

Compliance costs for regulatory approval could be prohibitive for many developing-country institutions.

have also evolved, such as the donation of IP facilities and "humanitarian"-use type agreements as were done with Golden Rice™, with the threshold for humanitarian versus commercial use being a $10,000 income from the technology. As the issue of IP rights becomes increasingly important, strenghthening of capacities of governments and science sectors of many developing countries will be needed to understand, deploy, and negotiate regarding biotechnology. Rice biotechnology practitioners in Asia need to be trained on the intricacies of modern IP rights systems and on negotiating with institutions and companies for the purpose of accessing IP, and applying for IP protection. Alternatively, research institutions could establish IP units, not only for negotiating with other institutions and sectors, but also for registration of their own biotechnology processes and products.

Regulatory Requirements

National biosafety committees in developing countries have made impressive progress in the drafting and implementation of biosafety regulations for the importation and testing of transgenic crops; regulations for field tests are already in place in rice-growing countries such as China, India, Thailand, and the Philippines (Atanassov *et al.*, 2004). A looming issue, however, revolves around the compliance costs for regulatory approval: they could be prohibitive for many developing-country institutions. In the various studies cited by Atanassov *et al.* (2004), annual compliance costs, including those for initial greenhouse and field screening, field testing for environmental impact, and food safety, but excluding technology development costs, ranged from US$140,000 for a virus-resistant papaya in Brazil to US$830,000 for a virus-resistant potato in South Africa. For rice, an annual regulatory compliance cost of US$680,000 was estimated for a virus-resistant variety in Costa Rica (Sittenfeld, 2002) covering tests on molecular characterization and epidemiology, transgenic field trials, biosafety, IP rights, food-safety deployment, and gene flow. Given reduced NARS budgets, this could pose a major hurdle in the commercialization of rice biotechnology products from the public sector. It is hoped, however, that as knowledge and experience are gained by regulatory agencies, approval costs may decrease, both by reducing the number of required tests, and by shortening the length of experimentation. The latter would also avoid the risk of biotechnology products becoming irrelevant to farmers' needs due to long delays in approval (Atanassov *et al.*, 2004). In this regard, continuous training of personnel in regulatory bodies of developing countries on new biotechnology developments and approaches is necessary for them to make educated recommendations, as is envisioned in the Cartagena Biosafety Protocol (CBD, 2000). A well functioning regulatory system can hasten acceptance of biotechnology products by instilling public confidence that risk assessments are carefully done, science-based, and, therefore, reliable.

Biosafety and Food Safety

The benefits that biotechnology confers upon the environment include reduction in the use of agrochemicals and preservation of presently uncultivated and marginal lands and concomitantly of biodiversity due to increases in productivity in currently used arable lands. To sustain the rice agriculture resource base and avoid environmental disturbance, it is important to match new genes and biotechnology-derived varieties to the target environments (Atanassov *et al.*, 2004). In 2003, GM crops commercialized in the developing world were largely limited to insect-protected cotton in Argentina, China, India, Mexico, and South Africa (James, 2003, Figure 4); experience remains limited on safety assessments of GM food crops such as rice. Among developing countries, only four have approved a single transgenic event in a food crop (soybean in Brazil, the Czech Republic and Uruguay; and maize in the Philippines), two have approved two events (soybean and tomato in Mexico; soybean and maize in South Africa) and one (Korea) has approved three events (one in soybean and two in maize) (Atanassov *et al.*, 2004). Therefore, the sharing of experiences and knowledge from food-safety assessments done in these countries should be valuable for developing countries with rice-biotechnology products in the pre-commercialization stages. As rice is a food,

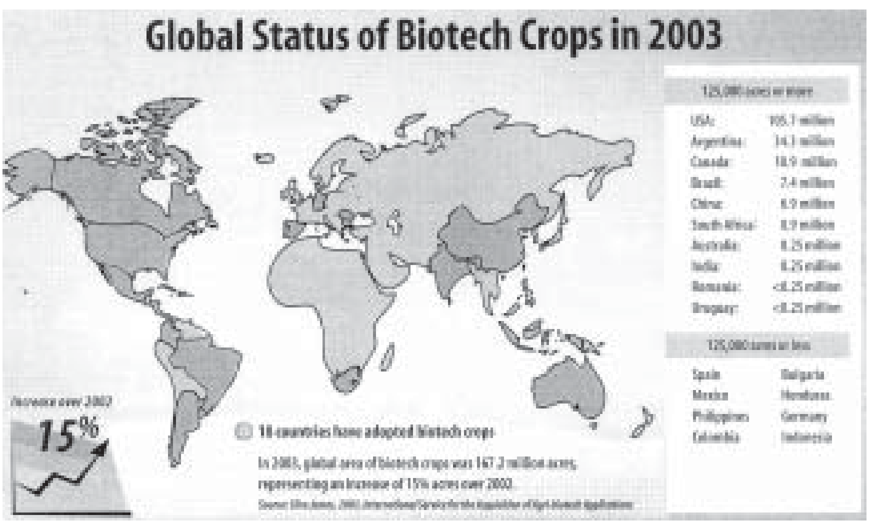

Figure 4. Global status of biotech crops in 2003 (James, 2003).

and *per-capita* consumption varies both within and among countries—from less than 100 kg/yr in China and India to over a 200 kg/year in Myanmar (Maclean *et al.*, 2002)—careful food-safety experimentation must be done in the case of nutrient-enhanced GM rice to remove any potential health dangers related to over-dosages; alternatively, effective GM-rice deployment strategies need to be developed.

Given all of these issues and challenges, lessons can be learned from the saga of Golden Rice™, as to the confluence of factors necessary for a rice-biotechnology product to be developed and commercialized for maximum impact. As detailed by Potrykus (2000), the Golden Rice™ project was made possible because of enabling factors such as:

- an environment supportive of independent research,
- strong institutional collaborative research partnerships,
- availability of the needed genes,
- support from donor institutions for strategic research for developing countries, and
- a highly motivated team of scientists willing to work on a pro-poor R&D agenda.

Potrykus further noted that the Golden Rice™ experience should:

- facilitate greater public acceptance of GM technology,
- encourage research investments in projects without guarantees of success,
- motivate research to be more food security- and less industry-focused,
- encourage free licensing for enabling technologies if used for humanitarian purposes, and
- motivate scientists to undertake projects relevant to the poor.

Rice production in Asia must increase from its current level of 545 Mt to 700 Mt by 2025 in order to feed an additional 650 million consumers while ensuring profitability for countless resource-poor farmers. Biotechnology—which has progressed rapidly to a point where transgenic rices are about to be commercialized—can help address these major challenges of guaranteeing food security while alleviating poverty in Asia.

Conclusion

Rice production in Asia must increase from its current level of 545 Mt to 700 Mt by 2025 in order to feed an additional 650 million consumers while ensuring profitability for countless resource-poor farmers. Biotechnology—which has progressed rapidly to a point where transgenic rices are about to be commercialized—can help address these major challenges of guaranteeing food security while alleviating poverty in Asia. New processes and second- and third-generation products of greater relevancy are also in the pipeline, expected to gain rapid acceptance both by farmers and the rice-consuming public. It is important to note, however, that biotechnology is not a panacea for achieving food security and sustainability of rice-based agricultural systems in Asia. The technology must address the existing and projected problems of small rice-farming communities and, at the same time, the dietary and health needs of more than half of the world's population. Furthermore, products must be designed so that they complement rather than replace existing practices, and enrich rather than disrupt the agroenviroments for which they are targeted for deployment.

The tasks ahead are gargantuan and the future—particularly for transgenic rice in Asia—remains uncertain. Full engagement of and dialogue amongst all stakeholders are needed at all levels, in the public, private, NGO, and other relevant sectors of society. New modalities of collaboration need to be explored. Asia must draw its lessons from cumulative experience in the developed world. Programs that stimulate open discussions and enable concerted and cooperative efforts to be made on the safe and relevant use of rice biotechnologies must be supported. Only then can the impact of science in general, and biotechnology in particular, be maximized for the benefit of the poor in Asia, through the attainment of stable and sustainable rice-based agriculture and household food and economic security.

References

AgBios (2004) Global status of approved genetically modified plants. http://www.agbios.com/dbase.php?action =Synopsis.

Aldemita RR *et al.* (2004) Biotechnology for rice improvement. PhilRice Technical Bulletin 8 15–22.

Arumuganathan K Earle ED (1991) Nuclear DNA content of some important plant species. Plant Molecular Biology Reporter 9 208–218.

Asian Development Bank (ADB) (2001) Agricultural Biotechnology, Poverty Reduction and Food Security. Manila, Philippines: Asian Development Bank.

Atanassov A *et al.* (2004) To Reach the Poor—Results From the ISNAR-IFPRI Next Harvest Study on Genetically Modified Crops, Public Research and Policy Implications, EPTD Discussion Paper No. 116. Washington DC: International Food Policy Research Institute.

Beyer P *et al.* (2002) Golden Rice: Introducing the beta-carotene biosynthesis pathway into rice endosperm by genetic engineering to defeat vitamin A deficiency. Journal of Nutrition 132 506S–510S.

Blair M *et al.* (2003) High resolution genetic mapping and candidate gene identification at the xa5 locus for bacterial blight resistance in rice (Oryza sativa L.). Theoretical and Applied Genetics 107 62–73.

Bouman BAM (2003) Examining the water-shortage problem in rice systems: water-saving irrigation technologies. In: Rice Science: Innovations and Impact for Livelihood (Mew TW Eds). Beijing: Chinese Academy of Engineering and Chinese Academy of Agricultural Sciences, Los Baños: International Rice Research Institute.

Brookes G Barfoot P (2003) GM Rice: Will this Lead the Way for Global Acceptance of GM Crop Technology? Brief No. 28. Los Baños: ISAAA.

Bruskiewich R *et al.* (2003) Linking genotype to phenotype: the International Rice Information System (IRIS). Bioinformatics 19 163–165.

Cantrell RP Hettel GP (2004) New Challenges and Technological Opportunities for Rice-Based Production Systems for Food Security and Poverty Alleviation in Asia and the Pacific. Presented at the FAO Rice Conference, FAO, Rome, Italy, February 12–13.

Champoux MC *et al.* (1995) Locating genes associated with root morphology and drought avoidance via linkage to molecular markers. Theoretical and Applied Genetics 90 969–981.

Chen M *et al.* (2002) An integrated physical and genetic map of the rice genome. Plant Cell 14 537–545.

Chen S *et al.* (2000) Improvement of bacterial blight resistance of 'Minghui 63', an elite restorer line of hybrid rice, by molecular marker-assisted selection. Crop Science 40 239–244.

Coffman R *et al.* (2004) Potentials and Limitations of Rice Biotechnology. Presented at the FAO Rice Conference, FAO, Rome, Italy, February 12–13.

Convention on Biological Diversity (CBD) 2000. Cartagena Protocol on Biosafety to the Convention on Biological Diversity. Montreal: Secretariat to the Convention on Biological Diversity.

Datta K *et al.* (2003) Bioengineered "golden" indica rice cultivars with beta-carotene metabolism in the endosperm with hygromycin and mannose selection systems. Plant Biotechnology Journal 1 81–90.

Deparment for International Development (DFID) (2004) Rice Biotechnology: Towards Sustainable Agriculture in the Developing World. Bangor: DFID. http://www.dfid-psp.org/publications/biotech/RiceRpt.pdf.

Evenson RE (Eds) (1996) Rice Research in Asia: Progress and Priorities. Manila: International Rice Research Institute and Wallington: CAB International.

Food and Agriculture Organization (FAO) 2004. Rice is Life. Italy: FAO. http://www.fao.org/newsroom/en/focus/200436887/ index.html.

Feng QY *et al.* (2002) Sequence and analysis of rice chromosome 4. Nature 420 316–320.

Flowers TJ *et al.* (2000) QTL: their place in engineering tolerance of rice to salinity. Journal of Experimental Botany 51 99–106.

Garg AK *et al.* (2002) Trehalose accumulation in rice plants confers high tolerance levels to different abiotic stresses, Proceedings of the National Academy of Sciences 99 15898–15903.

Goff SA (2002) A draft sequence of the rice genome (Oryza sativa L. ssp. japonica). Science 296 92–100.

Gregorio GB (2002) Progress in breeding for trace minerals in staple crops. Journal of Nutrition 132 500S–502S (review).

Herdt RW (1991) Research priorities for rice biotechnology. In: Rice Biotechnology (Khush GS Toenniessen GH Eds). Wallingford: CAB International and Los Baños: International Rice Research Institute, 19–54.

Herdt R (1997) The Future of the Green Revolution: Implications for International Grain Markets. Bozeman: Trade Research Center, Montana State University.

Hossain M (1997) Rice supply and demand in Asia: A socioeconomic and biophysical analysis. In: Applications of Systems Approaches at the Farm and Regional Levels (Teng PS *et al.* Eds). Dordrecht: Kluwer Academic Publishers.

Huang N *et al.* (1997) Pyramiding of bacterial blight resistance genes in rice: marker-assisted selection using RFLP and PCR. Theoretical and Applied Genetics 95 313–320.

International Rice Research Institute (IRRI) (2001) Water. In: Rice research: The Way Forward, IRRI Annual Report, 2000–2001. Manila: International Rice Research Institute, 17.

International Service for the Acquisition of Agri-biotech Applications (ISAAA) (2004a) GM Rice/Golden rice. Manila: ISAAA. http://www.isaaa.org.

International Service for the Acquisition of Agri-biotech Applications (ISAAA) (2004b) GM Rice/Iron-rich rice. Manila: ISAAA. http://www.isaaa.org.

James C (2003) Preview: Global Status of Commercialized Transgenic Crops: 2003, ISAAA Briefs No. 30. Ithaca, NY: ISAAA.

Jia H *et al.* (2004) China ramps up effort to commercialize GM rice. Nature Biotechnology 22 642.

Khush G (2004) Harnessing Science and Technology for Sustainable Rice Based Production Systems. Presented at the FAO Rice Conference, Rome, Italy, February 12–13.

Komari T *et al.* (1998) Advances in cereal gene transfer. Current Opinions in Plant Biology 1 161–165.

Leung H *et al.* (2004) Sustainable Disease Resistance in Rice: Current and Future Strategies. Presented at the 4th International Crop Science Congress, Brisbane, Australia.

Maclean JL *et al.* (Eds) (2002) Rice Almanac. Los Baños: International Rice Research Institute, Bouake; Ivory Coast: West Africa Rice Development Association; Cali: International Center for Tropical Agriculture; Rome: Food and Agriculture Organization.

McCouch SR *et al.* (1988) Molecular mapping of rice chromosomes. Theoretical and Applied Genetics 76 815–829.

McCouch S *et al.* (2002) Development of 2,240 new SSR markers for rice (Oryza sativa L.). DNA Research 9 199–207.

Nguyen VN (2002) Productive and environmentally friendly rice integrated crop management systems. IRC Newsletter 51 25–32.

Nuffield Council on Bioethics. 2004. The Use of Genetically Modified Crops in Developing Countries: A Follow-Up Discussion Paper. London: Nuffield Council on Bioethics.

O'Toole JC *et al.* (2001) The Rockefeller Foundation's international program on rice biotechnology. In: Rice Genetics IV (Khush GS *et al.* Eds). New Delhi: Science Publishers and Los Baños, Philippines: International Rice Research Institute, 39–62.

Papademetriou MK (1999) Rice Production in the Asia-Pacific Region: Issues and Perspectives. Regional Expert Consultation on Bridging the Rice Yield Gap in the Asia and Pacific Region, at the FAO Regional Office for Asia and the Pacific, Bangkok, Thailand, October 5–7.

Potrykus I (2000) The Golden Rice™ Tale. AgBio View: http://agbioview.listbot.com.

Price AH *et al.* (2002) Mapping QTLs associated with drought avoidance in upland rice grown in the Philippines and West Africa. Plant Molecular Biology 48 683–695.

Redoña ED Mackill DJ (1996) Mapping quantitative trait loci for seedling vigor in rice using RFLPs. Theoretical and Applied Genetics 92 395–402.

Redoña ED *et al.* (2003) Hybrid rice development and use in the Philippines, 1998–2001. In: Hybrid Rice for Food Security, Poverty Alleviation, and Environmental Protection (Virmani SS *et al.* Eds). Los Baños: International Rice Research Institute.

Ronald P *et al.* (1992) Genetic and physical analysis of the rice bacterial blight disease resistance locus, XA21. Molecular and General Genetics 236 113–120.

Sasaki T *et al.* (2002) The genome sequence and structure of rice chromosome 1. Nature 420 312–316.

Sittenfeld A (2002) Agricultural biotechnology in Costa Rica: status of transgenic crops. In: Next Harvest—Advancing Biotechnology's Public Good: Technology Assessment, Regulation and Dissemination. The Hague, Netherlands: ISNAR.

Song WY *et al.* (1995) A receptor kinase-like protein encoded by the rice disease resistance gene, Xa21. Science 270 1804–1806.

Takeuchi Y *et al.* (2003) Fine linkage mapping enables dissection of closely linked quantitative trait loci for seed dormancy and heading in rice. Theoretical and Applied Genetics 107 1174–1180.

Tanticharoen M (1997) Thailand: Biotechnology for Farm Products and Agro-Industries. http://www.cgiar.org/biotech/rep0100/Tanticha.pdf.

The Rice Chromosome 10 Sequencing Consortium (2003) In-depth view of structure, activity, and evolution of rice chromosome 10. Science 300 1566–1569.

Thomson M *et al.* (2003) Mapping quantitative trait loci for yield, yield components and morphological traits in an advanced backcross population between Oryza rufipogon and the Oryza sativa cultivar Jefferson. Theoretical and Applied Genetics 107 479–493.
Tuong TP, Bouman BAM (2002) Rice production in water scarce environments. In: Water Productivity in Agriculture: Limits and Opportunities for Improvement. The Comprehensive Assessment of Water Management in Agriculture Series, Volume 1 (Kijne JW *et al.* Eds), Wallingford: CABI Publishing, 13–42.
Vasconcelos M *et al.* (2003) Enhanced iron and zinc accumulation in transgenic rice with the ferritin gene. Plant Science 164 371–378.
Virmani SS (2003) Advances in hybrid rice research and development in the tropics. In: Hybrid Rice for Food Security, Poverty Alleviation, and Environmental Protection (Virmani SS et al. Eds). Los Baños: International Rice Research Institute.
Wang GL *et al.* (1995) Construction of a rice bacterial artificial chromosome library and identification of clones linked to the Xa-21 disease resistance locus. Plant Journal 7 525–533.
Wu J *et al.* (2002) A comprehensive rice transcript map containing 6591 expressed sequence tag sites. Plant Cell 14 525–535.
Xu K Mackill DJ (1996) A major locus for submergence tolerance mapped on rice chromosome 9. Molecular Breeding 2 219–224.
Yu J *et al.* (2002) A draft sequence of the rice genome (*Oryza sativa* L. ssp *indica*). Science 296 79–92.
Zhang S *et al.* (1998) Transgenic elite indica rice varieties, resistant to Xanthomonas oryzae pv. orzae. Molecular Breeding 4 551–558.

EDILBERTO D. REDOÑA is the deputy executive director for research and development of the Philippine Rice Research Institute (PhilRice) in Muñoz, Nueva Ecija, Philippines. PhilRice is the lead national and coordinating agency for all publicly funded R&D rice activities.

An MS and PhD graduate in genetics from the University of California, Davis—through a Rockefeller Foundation fellowship—Redoña is president of the Crop Science Society of the Philippines, and editor of the *Journal* *of Breeding and Genetics*, a publication of the Society for the Advancement of Breeding Research in Asia and Oceania (SABRAO). He chairs the Technical Working Group of the Open Academy for Philippine Agriculture, an alliance of seventeen institutions aiming to empower farmers and extension agents through ICT-based learning approaches.

With 20 years experience in rice research, Redoña's foremost interests include the application of molecular markers and biotechnology in breeding, and development of hybrid rices. His contributions in these endeavors garnered him the Outstanding Young Scientist Award from the Philippine National Academy of Science and Technology, and the Outstanding Researcher and Best Research Awards from the Philippine Department of Agriculture. He leads the commercialization of hybrid rice technology, the Philippine government's banner program for agriculture.