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What it will take to Feed 5.0 Billion Rice consumers in 2030

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Abstract

Major advances have occurred in rice production due to adoption of green revolution technology. Between 1966 and 2000, the population of densely populated low income countries grew by 90% but rice production increased by 130% from 257 million tons in 1966 to 600 million tons in 2000. However, the population of rice consuming countries continues to grow and it is estimated that we will have to produce 40% more rice in 2030. This increased demand will have to be met from less land, with less water, less labor and fewer chemicals. To meet the challenge of producing more rice from suitable lands we need rice varieties with higher yield potential and greater yield stability. Various strategies for increasing the rice yield potential being employed include: (1) conventional hybridization and selection procedures, (2) ideotype breeding, (3) hybrid breeding, (4) wide hybridization and (5) genetic engineering. Various conventional and biotechnology approach are being employed to develop durable resistance to diseases and insect and for tolerance to abiotic stresses. The availability of the rice genome sequence will now permit identification of the function of each of 60,000 rice genes through functional genomics. Once the function of a gene is identified, it will be possible to develop new rice varieties by introduction of the gene through traditional breeding in combination with marker aided selection or direct engineering of genes into rice varieties.

Rice is the world's most important food crop and a primary source of food for more than half the world's population. More than 90% of the world's rice is grown and consumed in Asia where 60% of the earths' people live. Rice accounts for 35–75% of the calories consumed by more than 3 billion Asians. It is planted on about 154 million hectares annually or on about 11% of the world's cultivated land.

Rice is probably the most diverse crop. It is grown as far north as Manchuria in China and far south as Uruguay and New South Wales in Australia. Rice grows at more than 300 m elevations in Nepal and Bhutan and 3 m below sea level in Kerala in India. Major advances have occurred in rice production during the last four decades due to adoption of green revolution technology. Between 1966 and 2000, the population of densely populated low income countries grew by 90% but rice production increased by 130% from 257 million tons in 1966 to 600 million tons in 2000. In 2000, the average per capita food availability was 18% higher than in 1966. The technological advance that led to dramatic achievements in world food production during last 40 years was the development and wide scale adoption of high yielding and disease and insect resistant varieties of rice. The adoption of green revolution technology was facilitated by: (1) development of irrigation facilities; (2) availability of inorganic fertilizers; and (3) benign government policies.

In spite of these advance in food grain production 800 million people, mostly in developing countries go to bed hungry everyday.

Micronutrient deficiencies affect 3 billion people. Every 36 s somebody dies of hunger. Chronic hunger takes the lives of 2400 people everyday, 13 million children under the age of five die because of hunger and malnutrition, and one out of five babies is born underweight. Malnutrition hinders the development of human potential and the nation's social and economic development.

Rice scenario in new millennium

According to various estimates we will have to produce 40% more rice by 2030 to satisfy the growing demand without affecting the resource base adversely. These estimates are based in view of continued population growth, a drastic reduction in growth of rice production during 1990s (Brown, 1996; 1997) and economic prosperity.

Population

According to UN estimates, the world population will grow from 6 billion in 2000 to 8 billion in 2025. Most of this increase (93%) will take place in the developing world, whose share of population is projected to increase from 78% in 1995 to 83% in 2020. The annual rate of world's population growth reached its historical high in 1964 at 2.2%. Since then, it has been slowly declining, dropping to 1.4% in 1998. Despite the falling rate of growth, the annual increase in the world's population was 72 million in 1964, reaching an all time high of 87 million in 1990, falling to 80 million in 1997. It is expected to remain at the 80 million level for the next two decades before it starts to decline (U.S. Bureau of Census, 1998).

The population projections for individual countries vary more widely than at any time in history. Population has stabilized in some 32 countries, while it continues to grow in some countries at the rate of 3% per year. With the exception of Japan, all the nations in the first group are in Europe and all are industrial countries. The population of some countries such as Russia, Japan and Germany are actually projected to decline over the next 50 years. In contrast to this group some countries are projected to triple their populations by 2050. For example, Ethiopia's current population of 62 million will be more than triple by 2050. Pakistan's population is projected to grown from 148 million to 357 million, surpassing that of the USA before 2050. Nigeria meanwhile is projected to grow from 122 million at present to 339 million giving it a higher population in 2050 than for whole of Africa in 1950.

Cereal Production

The relationship between growth in world's population and the grain production has shifted over the last half century, neatly dividing this period into two distinct eras. From 1960 to 1985, growth in grain production easily exceeded that of population, raising the harvest per capita from 279 kg in 1960 to 343 kg in 1985. During the next 15 years, the growth in grain production fell behind that of population growth. The slower growth in world grain harvest is due to slower growth in irrigation and fertilizer use. The irrigated area per capita after expanding by 30% from 1950–1978 has declined by 4%. Since then growth in irrigated area has fallen behind that of population growth (Postel, 1997). The increase in fertilizer use has slowed dramatically since 1990, as diminishing returns following the application of additional fertilizer have stabilized use in USA, Western Europe and Japan and slowed annual growth in world fertilizer use from 6% between 1950 and 1990 to only 2% in recent years (Soh and Isherwood, 1997).

Changing food habits

The most important factor that influences per capita consumption of staple grains is the level of income of the consumer. At low levels of income, meeting energy needs is the most basic concern of an individual. Staple foods such as starchy roots, rice, wheat and other cereals provide cheapest source of energy. Low income consumers spend most of their income on this type of food. As income increases, the consumer shift from low quality to better quality products. For example, rice is the most preferred staple in Asia where 90% of the world's rice is produced. At low levels of income, rice is considered a luxury commodity. At times of scarcity, when incomes are very low, consumers are often satisfied with coarse grains and sweet potatoes, which are cheapest source of energy. As incomes grow, per capita rice consumption increases, with consumer's substituting rice for coarse grains and root crops. However, as income increases beyond a threshold, consumers can afford to have a high value balanced diet containing foods that provide more proteins and vitamins such as vegetables, fruits, fish and livestock products and the per capita rice consumption starts to decline. This pattern of change in food consumption with economic growth is amply demonstrated by the experience of Japan and Korea, which made a transition from low to a high income level within a short period of time. The rice consumption in Japan increased with economic growth after Second World War, reached a peak of about 120 kg per person per year in early 1960s and then started to decline. By late 1980s per capita rice consumption was 40% lower than that in 1960s (Hossain and Sombilla, 1999).

In many countries in East and Southeast Asia, income has reached a level where we expect the per capita rice consumption to decline in near future. The Food and Agriculture Organization (1996) data show that among Asian countries, per capita rice consumption has declined substantially in Japan, South Korea, Taiwan, Malaysia and Thailand, all middle and high-income countries that have passed the income threshold mentioned earlier. However, the per capita rice consumption in most of the other countries of Southeast and South Asia is going up. Moreover, as the poverty alleviation programs succeed the purchasing power of the poor will increase and so will the demand for rice.

Feeding 5 billion rice consumers in 2030

As mentioned earlier we will have to produce 40% more rice by 2030 to satisfy the growing demand without affecting the source base adversely. This increased demand will have to be met from less land, with less water, less labor and fewer chemicals. If we are not able to produce more rice from the existing land resources, land hungry farmers will destroy forests and move into more fragile lands such as hillsides and wetlands with disastrous consequences for biodiversity and watersheds. To meet the challenge of producing more rice from suitable lands we need rice varieties with higher yield potential and greater yield stability.

Increasing the yield potential of rice

Various strategies for increasing the yield potential of rice are being employed. These include: (1) conventional hybridization and selection procedures, (2) ideotype breeding, (3) hybrid breeding, (4) wide hybridization and (5) genetic engineering.

Conventional hybridization and selection procedures

Improvements in the yield potential of crops have been achieved through conventional hybridization and selection procedures. It is estimated that on the average about 1% increase has occurred per year in the yield potential of rice over a 35-year period since the development of first improved variety of rice IR8 (Peng *et al.*, 2000). There is no reason to believe that such increases will not occur in the future if sufficient investment in research is made.

Ideotype breeding

Ideotype breeding aimed at modifying the plant architecture is a time tested strategy to achieve increases in yield potential. As an example selection for short stature cereals such as wheat, rice and sorghum resulted in doubling of yield potential. Introduction of *sd*1 gene for short stature into rice led to improvement in harvest index from 0.3 to 0.5 and increases in biomass production.

To increase the yield potential of rice further, a new plant type was conceptualized in 1988. Modern semi-dwarf rices produce a larger number of unproductive tillers and excessive leaf area which cause mutual shading and reduce canopy photosynthesis and sink size, especially when they are grown under direct sowing conditions. To increase the yield potential of these semi-dwarf rices further, IRRI scientists proposed further modifications of plant architecture with following characteristics:

- Low tillering (9–10 tillers when transplanted)
- No unproductive tillers
- 200–250 grains per panicle
- Dark green and erect leaves
- Vigorous and deep root system

Breeding efforts to develop "New Plant Type" (NPT) were initiated in 1990. The objective was to develop improved germplasm with 15–20% higher yield than that of existing high yielding varieties. Numerous breeding lines with desired ideotype were developed (Khush, 1995) and were shared with national rice improvement programs. Three NPT lines have been released in China and one in Indonesia. Other NARS (National Agricultural Research Systems) are evaluating and further improving the NPT lines.

Hybrid breeding

The yield potential of maize has been improved through the development of hybrid varieties. The F_1 hybrids on the average yield 15% more than the cultivars (Tollenaar, 1991). Heterosis (first generation hybrid vigor) has also been exploited to increase the yield potential of sorghum, pearl millet and more recently of rice. Rice hybrids with a yield advantage of 10–15% are now widely grown in China. Rice hybrids adapted to tropics and subtropics have been developed at the International Rice Research Institute (IRRI) and by the national rice improvement programs. Various strategies are being being employed to raise the level of Heterosis. Efforts are underway to identify heterotic groups within the indica germplasm. Another approach is to develop improved tropical japonica germplasm. It is likely that hybrids between improved indicas and improved tropical japonicas will have higher level of Heterosis. When rice hybrids are adopted widely they will impact the rice production in tropical and subtropical Asia.

Wide hybridization

Crosses between crop cultivars and wild species, weedy races as well as intra-specific groups lead to widening of gene pools. Such gene pools are exploited for improving many traits including yield potential. Lawrence and Fry (1976) selected progenies with increased yield potential from crosses of cultivated oats, *Avena sativa* and wild oats *Avena sterilis*. Xiao *et al.* (1996) reported that some backcross derivatives from a cross between an *Oryza rufipogon* accession from Malaysia and cultivated rice, outyielded the recurrent parent by as much as 18%. They identified two QTL from wild rice with major contribution to yield increase. These QTL are now being transferred to several modern semi-dwarf varieties. Molecular marker assisted backcrossing is a useful approach for bringing alleles for yield improvement from wild germplasm.

Genetic engineering

Since protocols for rice transformation are well established (Christou *et al.*, 1991), it is now possible to introduce single alien genes that can selectively modify yield determining processes. In several crop species incorporation of "stay green" trait or slower leaf senescence has been a major achievement of breeders in the past decades (Evans, 1993). In some genotypes with slower senescence (stay green), the rusbico degradation is slower which results in longer duration of canopy photosynthesis and higher yields. The onset of senescence is controlled by a complement of external and internal factors. Plant hormones such as ethylene and abscisic acid promote senescence, while cytokinins are senescence antagonists. Therefore, over production of cytokinins can delay senescence. The *ipt* gene from *Agrobacterium tumefacions* encoding an isopentenyl transferase (Akiyoshi *et al.*, 1984) was fused with senescence-specific promoter SAG 12 (Gan and Amasino, 1995) and introduced into tobacco plants. The leaf and floral senescence in the transgenic plants was markedly delayed, biomass and seed yield was increased but other aspects of plant growth and development were normal. This approach appears to have great potential in improving canopy photosynthesis and increasing the yield.

Breeding for durable resistance

Diseases and insects take serious toll of crop production. According to FAO estimates, diseases, insects and weeds cause as much as 25% yield losses annually in cereal crops. Similarly crop yields are reduced and fluctuate greatly as a result of abiotic stresses such as drought, excess water (submergence), mineral deficiencies and toxicities and abnormal temperatures. Plant breeders have been improving the crops to withstand these biotic and abiotic stresses to impart yield stability.

Diverse sources of resistance to major diseases and insects have been identified and rice varieties with multiple resistance to diseases and insects have been developed. Recent breakthroughs in cellular and molecular biology have provided tools to develop more durable resistant cultivars and to overcome the problem of lack of donors for resistance to some diseases and insects such as sheath blight and stemborers.

Yellow stemborer is widespread pest in Asia and causes substantial crop losses. Improved rice cultivars are either susceptible to the insect or have only partial resistance. Codon optimized *Bt* gene was introduced into rice and the transgenic rices showed excellent levels of resistance in the laboratory as well as in the field (Datta *et al.*, 1997). *Bt* rices have also been tested under field conditions in China (Tu *et al.*, 2000) and showed excellent resistance to diverse populations of stemborer. Besides *Bt* genes, other genes for insect resistance such as those for proteinase inhibitors, *a*-amylose inhibitors and lectins are also beginning to receive attention.

Two of the most serious and widespread diseases in rice production are rice blast caused by the fungus *Pyricularia Oryzae* and bacterial blight caused by *Xanthomonas Oryzae pv. oryzae*. Development of durable resistance to these diseases is the focus of a coordinated efforts at IRRI using molecular marker technology. Efforts to detect markers closely linked to bacterial blight resistance genes have taken advantage of the availability of near isogenic lines having single genes for resistance. Segregating populations were used to confirm cosegregation between RFLP markers and genes for resistance. Protocols for converting RFLP markers into PCR based markers and using the PCR markers in marker-aided selection (MAS) have been established (Zheng *et al.*, 1995). The PCR markers were also used for pyramiding genes for resistance to bacterial blight. Thus *Xa4*, *xa5*, *xa13* and *Xa21* were combined into same breeding line (Huang *et al.*, 1997). Pyramided lines showed a wider spectrum and higher level of resistance. MAS has also been employed for moving genes from pyramided lines into new plant type (Sanchez *et al.*, 2000), as well as into improved varieties grown in India (Singh *et al.*, 2001). Xa 21 has also been introduced into widely grown rice varieties through genetic engineering. Transgenic lines are being evaluated under field conditions.

Breeding for abiotic stress tolerance

A series of stresses such as drought, excess water, mineral deficiencies and toxicities in soil and unfavorable temperatures affect rice productivity. The progress in developing crop cultivars for tolerance to abiotic stresses has been slow because of lack of knowledge of mechanisms of tolerance, poor understanding of inheritance of resistance or tolerance. Low heritability, lack of efficient techniques for screening the germplasm and breeding materials. A few cultivars with varying degrees of tolerance to abiotic stresses have been developed. Rainfed rice is planted to about 40 million hectares worldwide. Vast areas suffer from drought at some stage of growth cycle. QTL for various component traits for drought tolerance have been mapped (Champoax *et al.*, 1995) and information is being utilized to develop improved cultivars with drought tolerance.

Genetic engineering techniques hold great promise for developing rice with drought tolerance. Garg *et al.*, (2002) introduced *otsA* and *OtsB* genes for trehalose biosynthesis from *Escherichia coli* into rice and transgenic rices accumulated trehalose at 3–10 times that of non-transgenic controls. Trehalose is a non-reducing disaccharide of glucose that functions as compatible solute in the stabilization of biological structures under abiotic stress. The transgenic rice lines had increased tolerance for abiotic stresses such as drought and salinity.

Rice breeding in genomics era

Recent breakthroughs in deciphering the genetic code of rice have brought this cereal crop of the world's poor to the center stage of genomics. The International Rice Genome Sequencing project (IRGSP) sequence published in 2002 will serve as a gold standard for all future investigations of genetic variation in crops. This sequence of rice genome will benefit many other species particularly cereals such as wheat, maize, sorghum and barley. Comparative genomic analysis will help assign a tentative gene function to a gene according to what that gene does in another species. The availability of rice genome sequence will now permit identification of the function of each of 60,000 rice genes through functional genomics. Once the function of a gene is verified, it will be possible to develop new rice varieties by introduction of the gene through traditional breeding in combination with marker aided selection or direct engineering of the gene into rice varieties or even other cereals. Knowing the sequence of specific genes will allow us to tap into natural genetic variation of a crop species. There are over 100,000 accessions of traditional rice varieties collected from range of geoclimates. These seeds serve as a pool of natural variants. To date this wealth of germplasm has remained largely untapped owing to difficulty of identifying agronomically important genes. Now if a gene is proven to contribute to traits of agronomic importance, alleles of this gene can be examined from multiple varieties for their relative usefulness. Thus applying the information to rice improvement will require integrated approaches using diverse germplasm, traditional breeding, modern technologies and emerging knowledge from comparative genomics.

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