Genetic enhancement for higher yield potential and greater yield stability in rice

Darshan S. Brar[1], Parminder S. Virk, and Fangming Xie

[1]International Rice Research Institute, www.irri.org, E-mail: d.brar@cgiar.org

Abstract

During the last few decades, world rice production has more than doubled from 256 to 600 million tons. However, we need to produce 25% more rice to meet future demand. Plant breeders, therefore, are facing two major challenges 1) to produce more rice with less land, less water, less chemicals and less labor and 2) to overcome yield instability due to several biotic and abiotic stresses particularly as a consequence of climatic change. We need to develop genetically superior varieties with higher yield potential, higher yield stability and greater production efficiency. Recent advances in molecular biology particularly genomics in combination with conventional plant breeding approaches offer new opportunities to overcome above constraints and in enhancing yield potential of rice varieties. Some of the breeding strategies include 1) incorporation of genetic diversity involving diverse crosses - indica x japonica, indica x tropical japonica etc. and generating new plant types with high yield potential and high production efficiency. This approach is being pursued and has been used to develop varieties with 10-15% higher yield than the semi-dwarf varieties 2) exploitation of heterosis and develop hybrid rice varieties with 15-20% higher yield level of the existing inbred cultivars 3) identification and introgression of yield enhancing loci from wild species 4) modifying starch biosynthesis through transfer of *glg*C16 gene into rice may help to increase yield potential and 5) developing C4 rice offers yet another opportunity of enhancing yield potential. Furthermore, genetic improvement for tolerance to environmental stresses will contribute to greater yield stability.

Media summary

Enhancing yield potential of rice cultivars would lead to greater food security in developing countries.

Keywords

Yield potential, heterosis, new plant types, wild species, C4, rice

Introduction

Plant physiologists have suggested that a physical environment in the tropics is not a limiting factor to increasing rice yields. Maximum yield potential was estimated to be 9.5 t ha^{-1} in the wet season (WS) and 15.9 t ha^{-1} in the dry season (DS) (Yoshida 1981). Yield potential of current high yielding rice varieties in the tropics is 10t ha^{-1} during DS and 6.5 t ha^{-1} during WS. Quantum jumps in the yield potential of cereal varieties contributing to green revolution have resulted from the modification of plant ideotypes (Khush, 1995). To further increase the yield potential, we must explore the possibility of modifying the plant architecture of high yielding varieties. Another approach for increasing yield potential of rice is exploitation of hybrid vigor or heterosis.

New plant types for increased yield potential

Yield is a function of total dry matter (biomass) and harvest index of modern high yielding varieties is around 0.5. It should be possible to raise the harvest index to 0.6. High yielding varieties produce a total biomass of about 20 t ha^{-1} under optimum conditions. By raising the biomass to about 22t ha^{-1} and harvest index to 0.6, it should be possible to obtain yields of over 13 t ha-1. Such a plant type was conceptualized and breeding work on new plant type (NPT) was initiated in 1989 at IRRI (Khush, 1995). Optimum canopy architecture for maximum crop photosynthesis capacity of individual leaves, and delayed leaf senescence along with sink size, traits are important for increasing yield potential. Extensive breeding efforts involving crosses with tropical japonica resulted into an array of prototypes. Three varieties (Dianchao1, Dianchao 2, Dianchao3) originating from IRRI bred NPT elite lines have been released in China. Dianchao3 yielded as high as 16.2t ha $^{-1}$ at Taoyuan Township, Yongsheng County in Yunnan Province, which is the famous place for high yield in rice.

The high yielding NPTs in Tropical background lacked the grain quality preferred by many rice consumers in Asian countries. Thus, to improve the grain quality (long slender, medium slender grains) of NPTs, new crosses were made with elite indica parents. As a result of intensive breeding, numerous NPT lines with improved grain characteristics in the indica background have been bred (Virk and Khush, 2004). Some of the indica lines with >15% yield increase over the check varieties are given in Table1. During 2006, one of the NPT lines in the indica background namely IR77186-122-2-2-3 has been released as a national variety 'NSICRc 158 in the Philippines. Future research should focus on increasing harvest index using an array of plant types (2) enhancing yield involving plant types with different canopy and leaf characteristic based on selection for physiological traits (3) involving diverse crosses between subspecies and crosses involving lines with high biomass and those with bigger and heavier panicles.

Table 1. Performance of improved indica lines with >15% yield advantage over check varieties during 2006, DS at IRRI.

			Reaction to pests						**Quality traits**	
Designation	**Grain Yield (kg/ha)**	**Maturity (days)**	**BL**	**BB1**	**BB2**	**Tungro**	**GLH**	**BPH**	**Amylose**	**GT**
IR7915-42-1-3-1	6667	123	R	R	MS	S	MR	MR	I	HI/I
IR79218-93-1-4-3	7067	122	R	R	R	S	MR	MR	H	I
IR73718-23-2-1-3	6782	121	MS	R	MS	S	MR	MR	I	HI/I
IR79242-28-3-2-3	7501	120	MS	R	MS	S	MR	MS	I	HI/I
IR77700-84-2-2-2	7540	118	MS	R	MS	S	MR	MR	H	I
IR79193-83-1-1-1	6762	117	R	R	R	S	MR	MR	I	HI/I
IR78119-24-1-2-2-2	7237	114	MR	R	MS	R	MR	MR	I	HI/I
IR75386-14-3-2-2	6582	114	MR	R	MS	R	MR	MR	I	I
IR77734-93-2-3-2	6635	111	R	R	MS	S	MR	MS	I	HI/I
IR77512-128-2-1-2	7003	110	S	R	MS	S	MR	MR	I	HI/I

BL= blast; BB1= bacterial blight race1; BB2 =bacterial blight race 2; BHP =brown plant hopper; GLH= green leaf hopper; GT= gelatinization temperature; H=high; I=intermediate; R= resistant; MR= moderately resistant; MS= moderately susceptible; S=susceptible

Exploitation of heterosis for increasing yield potential

Heterosis has been successfully exploited to increase the yield potential of maize and sorghum. Utilization of heterosis in rice has become one of the main methods for increasing yield since 1970s. Rice hybrids with a yield advantage of 10-15% were introduced in China in the 1970s and are now planted in about 50% of the rice area in that country (Yuan, 2004). These hybrids performed poorly when evaluated in tropical countries. Thus, major efforts have been made to produce rice hybrids suitable for planting in the tropics and subtropics by IRRI and by national programs (Virmani, 2003). Hybrid rice is now grown in tropics on about 1.5 million hectares in India, Bangladesh, Philippines, Indonesia, Vietnam and other countries.

Selected hybrids also show a yield advantage of about 15% under tropical conditions. The increased yields of tropical rice hybrids are due to their increased total biomass, grain number per panicle, and, to some extent, higher grain weight as compared to their parents. Moreover, hybrids between indica and japonica varieties have a yield advantage of about 15-20%. It is hoped that NPT lines will have a yield potential of 12.5-13.0 t ha $^{-1}$ and the hybrids between NPT and indica lines will yield up to15 t ha $^{-1}$. Attempts are being made involving inter-varietal, inter-subspecific and distant hybridization to develop high yielding super hybrid rice varieties. The parental lines used in hybrid rice breeding are derivatives of indica x japonica crosses. The super high yield potential (11.4-12.2 t/ha) of Xieyou 9308 hybrid is an example of use of parents which are derivatives of crosses between indica and japonica subspecies of rice (Cheng et al., 2007).

Replacing 3-line with 2-line system which is more simple and efficient would be important in broadening genetic base of hybrid varieties. However, the reversion of male sterile lines by environmental factors: temperature and or photoperiod is not stable which need to be resolved. Another challenge is how to make a permanent hybrid or develop technique such as apomixis to fix hybrid vigor or any favourable gene combination. Future research in heterosis breeding should focus on (1) enhancing the level of hybrid varieties at least 10-15% over the best inbred check varieties (2) improving grain quality; cooking quality; grain appearance and reduced chalkiness (3) Developing stable two-line system to broaden the genetic base of hybrid varieties (4) identification of heterotic groups based on molecular diversity and intercrossing of such groups to obtain high level of heterosis (5) identification of QTLs and or heterotic gene blocks or regions on chromosomes which could increase heterosis in the hybrid combination and (6) Applying MAS to enhance the efficiency of hybrid rice breeding; examples include selection for fertility restoration, grain quality and pest resistance etc.

Introgression of yield enhancing loci/QTL from wild species

Wild species are phenotypically inferior (poor plant type, shattering susceptible, poor grain characteristics, low yield etc.) to cultivated species. These are important reservoir of useful genetic variation and many genes for tolerance to various biotic and abiotic stresses have been transferred from wild species into rice (Brar and Khush, 2006). Transgressive segregation for yield components from crosses with wild species has been observed. Molecular markers have made it possible to identify and introgress such QTLs from wild species into elite breeding lines. A number of studies have shown that introgression from wild species can result into transgressive segregation for yield and yield components. Such introgression has been attributed to the introgression of yield enhancing loci/QTLs from wild species into rice (Xiao, et al., 1996; Moncada, et al., 2001; Septiningsih, et al., 2003; Thomson, et al., 2006; Yoon et al., 2006).
Future research should focus to identify QTLs from wild species with larger effects for enhanced yield and introgress such QTLs into elite breeding lines of rice and determine their effect on yield potential in diverse high yielding genetic backgrounds.

Modification in starch biosynthesis

Starch biosynthesis plays a pivotal role in plant metabolism, both as a transient storage metabolite in leaf tissue and as an important energy and carbon reserve for sink organs, such as seeds, roots, tubers and fruit. Several enzymatic steps are involved in starch biosynthesis in plants. ADP-glucose pyrophosphorylase (ADPGPP) is critical enzyme in regulating starch biosynthesis in plant tissues. Even in storage organs with high levels of ADPGPP, its activity is still limiting. It should be possible to affect starch production in storage tissues positively by regulating the expression of the gene encoding this enzyme (Kishore 1994). Starch levels and dry matter accumulation were enhanced in potato tubers of plant transformed with the *glgC16* gene from *Escherichia coli* that encodes ADPGPP (Stark et al 1992) The transformed potato plants had tubers with higher dry matter and starch levels, under both growth chamber and field conditions. The *glgC16* gene, when introduced into rice through transformation, may help increase yield potential.

Development of C4 rice

To increase crop productivity, one of the option is to increase the photosynthetic efficiency; C4 (corn, sugarcane) photosynthesis system is more efficient than that of C3 (rice, wheat). C4 plants appear to have advantage over C3 in terms of photosynthetic efficiency and increased yield. Sheehy et al., (2000, 2007) have reviewed various strategies and challenges in the conversion of C3 to C4 rice.
Some laboratories have produced transgenic rice with C4 enzymes of maize (Ku et al., 1999). The transgenics did show expression of C4 enzymes; however, further studies are required to determine the agronomic performance and advantage over C3 plants in terms of yield increase. The pathways to success cannot be seen completely but it is likely that the new tools of genomics will be useful to construct C4 rice. It would require extensive experimentation and exploratory research on several basic components before C3 rice could be successfully converted as C4 for commercialization.

Selected references

Brar DS and Khush GS. 2006. Cytogenetic manipulation and germplasm enhancement of rice (*Oryza sativa* L.). Pages 115-158 In: Genetic Resources, Chromosome Engineering and Crop Improvement. Volume 2 (RJ Singh and PP Jauhar, eds.) CRC, Boca Raton, USA.

Khush GS. 1995. Breaking the yield frontiers of rice. GeoJournal 35:329-332.

Ku MS, Agarie S, Nomura M, Fukayama H, Tsuchida H, Ono K, Hirose S, Toki S, Miayo M and Matsuoka M. 1999. High-level expression of maize phosphoenol pyruvate carboxylase in transgenic rice plants. Nature Biotechnology 17:76-80

Stark DM, Timmerman KP, Barry GF, Preiss J, Kishore GM. 1992. Regulation of the amount of starch in plant tissues by ADP glucose pyrophosphorylase. Science 258:287-292.

Sheehy JE, Mitchell PL and Hardy B (eds). 2007. Charting new pathways to C4 rice. International Rice Research Institute, Manila, Philippines.

Virk PS and Khush GS. 2004. Breaking the yield barriers in rice. Pages 36-42. In: Proc. 1st Intern. Conference "Rice for the Future". Kasetsart University, Bangkok, Thailand.

Virmani, SS. 2003. Advances in hybrid rice research and development in the tropics. Pages 7-20. In: Hybrid Rice for Food Security, Poverty Alleviation and Environmental Protection (SS Virmani, CX Mao and B Hardy, eds.) International Rice Research Institute, Manila, Philippines.

Xiao J, Grandillo S, Ahn SN, McCouch SR, Tanksley SD, Li J, and Yuan LP. 1996. Genes from wild rice improve yield. Nature 384:223-224.

Yoshida S.1981. Fundamental of Rice Crop Science. International Rice Research, Manila, Philippines

Yuan LP. 2004. Progress in breeding of super hybrid rice. Pages 9-11. In: Proc. 1st Intern. Conference "Rice for the Future". Kasetsart University, Bangkok, Thailand.

.