International Journal of Bioinformatics and Biomedical Engineering
Vol. 1, No. 2, 2015, pp. 77-84
http://www.aiscience.org/journal/ijbbe

Modification of Rice Breeding Technology in 21st Century

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Abstract

Rice is a staple crop of more than one third of world's population. It is a major source of energy and carbohydrates. It is cultivated in maximum diverse environments that ranges from high hills to deep water, and probably still maintains larger variability than other crops. Thus rice has more diverse ecosystems and more challenges. Since the domestication of rice man has been engaged in improvement of it to meet his agro-ecological and socio-economic needs. To improve productivity of rice using conventional breeding is the most difficult task now due to narrow genetic base, less variability in the traits, dynamic nature of biotic and abiotice stresses, poor financial resources and support, changing climatic scenario and more labor oriented. New technology like biotechnology used in rice breeding program is a valuable tool in eliminating global hunger, poverty and malnutrition. It is a strategic weapon in winning the next Green Revolution. DNA marker technology has helped shortening breeding cycle and increase selection efficiency. Genetic Engineering also helps in exploiting variability across genus/species barriers. The main theme of this paper is that it is time to change breeding strategies. Breeders need to align, learn and apply the new technology in their breeding program. Breeders need to make sure that using diverse alleles will be one of the important components of their breeding program.

Keywords

Rice, Ecology, Breeding, Technology, Climate

Received: June 1, 2015 / Accepted: June 25, 2015 / Published online: July 16, 2015

1. Background

Rice is a staple crop of more than one third of world's population. It is a major source of energy and carbohydrates. It provides 20% of the world's dietary energy supply, while wheat supplies 19% and maize 5% (FAO, 2004). It provides 18.9% of calorie, 12.7% of protein per day intake of an individual (http://Nutritiondata.self.com). Unlike other cereals, rice is cooked and consumed as a whole grain and hence the grain characteristics assume special significance. Rice is cultivated in maximum diverse environments that ranges from hills to deep water and probably still maintains larger variability than other crops. Thus rice has more diverse ecosystems and more challenges (www.ricepedia.org). Globally rice is 2nd crop in terms of production after corn (FAOSTAT). It is a popular crop from rags to riches. The affinity of rice crop towards water is universally known. Rice

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requires 2-3 times more water as compared to other cereals (Tuong *et al* 2005). Conventional rice production ecosystems (puddled transplanted) require an average of 2500 liters of water to produce 1 kg of rough rice (Bouman *et al.,* 2007). It is also reported that about 50% of the diverted fresh water in Asia is used to irrigate rice fields (Barker *et al*., 1998). Majority of farmers in both irrigated and rainfed rice ecosystems grow rice in puddled transplanted conditions regardless of the topography and availability of irrigation water. Evapo-transpirational losses of water in rice are similar to wheat (Kumar and Ladha, 2011). Higher water requirements of rice are due to puddling, seepage and percolation losses associated with continuous flooding.

Re-discovery, elucidation and application of Mendel's Laws of inheritance was the defining moment in the history of biological sciences in general and crop improvement research in particular. Since the domestication of rice around 10,000 years back, man has been engaged in improvement of it to meet his agro-ecological and socio-economic needs (Molina *et al.,* 2011). Applying common sense initially by mass selection and later systematically by pureline selection in the heterogenous landraces he selected hundreds of cultivar strains of uniform stand with unique traits. Housing rich genetic variability for many a trait of economic value, the pureline varieties constitute till now the widely used 'cultivar genepool' in cross breeding research. Taichung (Native) 1, the Taiwan bred dwarf statured variety introduced in the mid 1960s marked the beginning of high yielding varieties; characterized by non lodging, dwarf habit, fertilizer responsiveness, early maturity and photo-insensitivity, the variety with doubled potential yield (10t/ha) breached the centuries long yield barrier. Rapid pace of its initial adoption ended soon on account of its high susceptibility to bacterial leaf blight. Replacement of it soon by IRRI-bred miracle yielder IR8 closely followed by India bred Jaya truly marked a major yield breakthrough. Extensive adoption of IR8 and Jaya along with a series of similarly tailored plant type varieties meeting diverse agro-ecological and socio-economic needs has led to 2.5 folds increase in rice production.

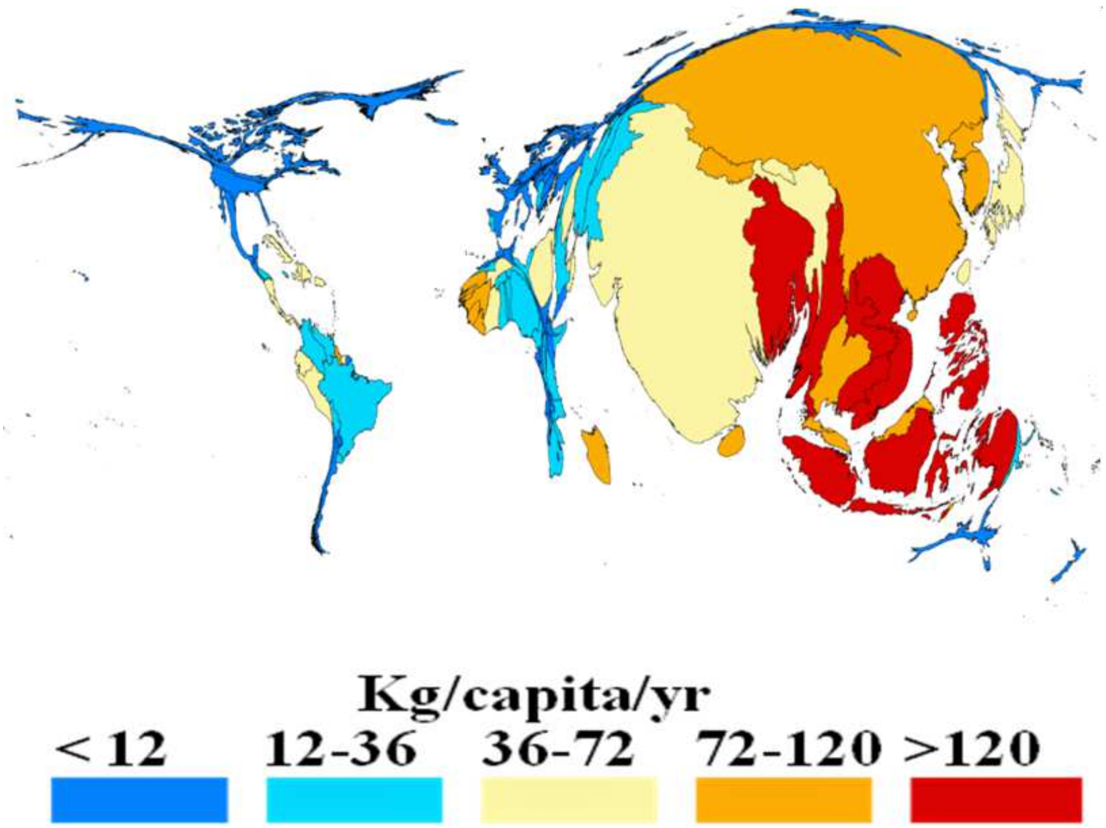

Fig. 1. Territory size represents the proportion of milled rice worldwide that is consumed in that territory. Color shows the per capita consumption of milled rice (Source: A. Nelson, IRRI; Food supply quantity data from FAOSTAT).

1.1. Recent Developments

Use of *sd1* dwarfing gene increased yield potential of irrigated rice (tropics) from 4-5 t ha^{-1} to 10 t ha^{-1} and brought green revolution in 1960s. Dry Direct Seeded Rice is an alternative way of rice transplanting that reduces water, labor, time and about 30% of total cost of wet tillage or puddling. Recently biotechnology is widely used in rice breeding program. It is a valuable tool in eliminating global hunger, poverty and malnutrition. It is a strategic weapon in winning the next Green Revolution.

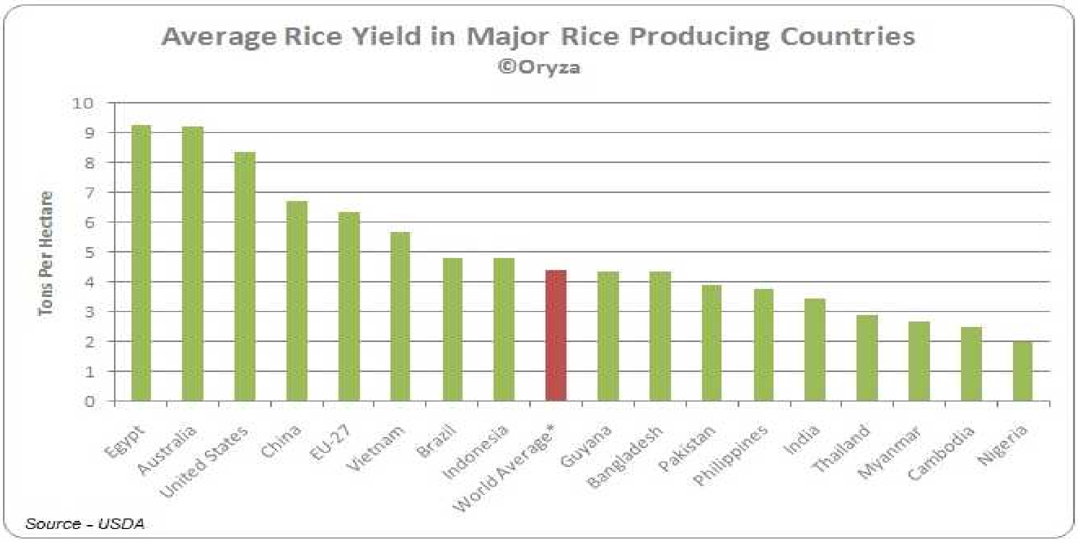

Fig. 2. Average rice yield in major rice producing countries.

1.2. Hybrid Rice

China developed first commercially viable hybrid rice technology by late 70s raising the potential yield to 12.5 t/ha than the best varieties and the technology found wide adoption over 80% of rice area. Simulation models predicted that a 25% increase in yield potential was possible by modification in the plant type for certain traits. Hybrid rice yields 15-20% more than Inbreds (IRRI, 2015). There is potential to increase yield beyond 10 t ha^{-1} in tropics.

1.3. Breeding for Super Rice

China launched the nationwide mega project in 1996 for breeding super rice varieties and hybrids with the objective of raising the ceiling to genetic yield to 15t/ha by 2015. Prof. Longpin Yuan initiated Super Rice Hybrid Breeding to exploit the highest hybrid vigour possible in intersubspecific (*indica*/tropical *japonica*) combinations in the IRRI's new plant type background. Two intersubspecific hybrids viz. Xieyou 9308 and Liangyoupeijiu in the NPT background with yield potential of >12.0t/ha are being extensively adopted in China.

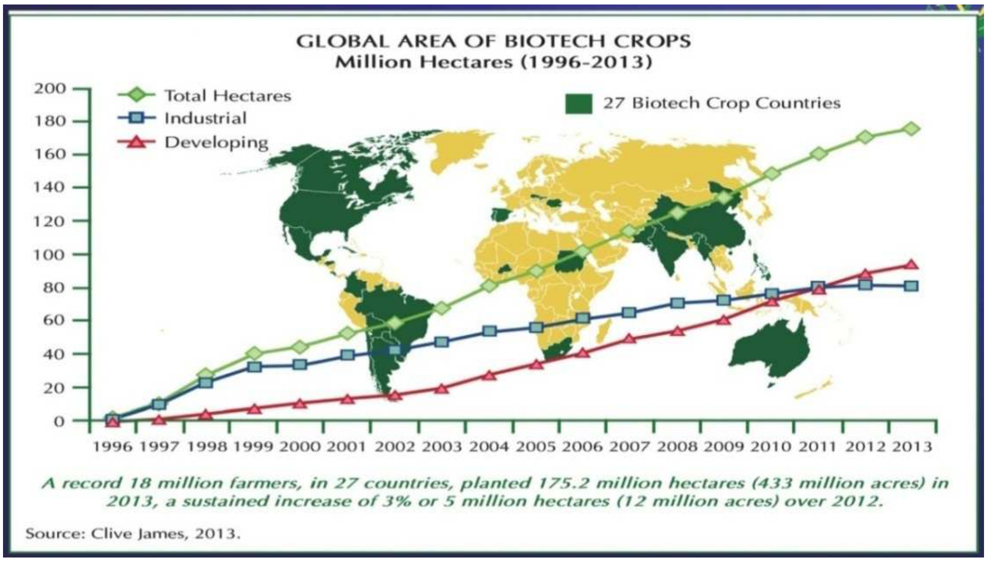

Fig. 3. Global production of Transgenic Crops, its Development & Deployment (source: Clive James, 2013).

1.4. Abiotic and Biotic Stress Tolerant Rice Varieties

Drought, salinity, submergence, temperature extremes and nutrient deficit soils are the major physical stresses, crops suffer from in general. Natural tolerance gene sources available in crop genepools have been identified and used to make crop varieties adapt to them and yield better. Valuable genes like SALTOL against salinity, sub1A against submergence, qDTY1.1 against drought, SNORKEL1 against deep water, PSBRc68 against stagnant flood, Qsct1 and qsct11 against low temperature, qAG9.1 against anaerobic germination, PSTOL against P deficiency in rice as well as against drought and qHTSF 1.1 against temperature rise in rice have been successfully mapped and tightly linked to functional markers for selective and speedy improvement of crops by marker assisted backcross breeding (Mackill, Glenn, R.K., Ye: IRRI, 2009).

Many rice varieties have been developed that are totally resistant to different rice diseases. Genes Pi9 and Pi40 are resistance to rice blast, genes Xa1-Xa27 resistance to bacterial leaf blight and $qBL_{12.1}$ resistance against brown spot. Many rice varieties are found resistance to different insects and pests also. Genes Gm4 and Gm8 are found resistance to gall midge.

1.5. Transgenic Crops

DNA marker technology helped shortening breeding cycle and increase selection efficiency. Genetic Engineering helps in exploiting variability across genus/species barriers. Through genetic engineering many transgenic/biotec crops have been developed and are being cultivated widely in different parts of the world.

2. Water Saving Rice Technologies

Several water saving rice technologies have been developed for rice cultivation such as Alternate wetting and drying (Li 2001; Tabbal *et al.,* 2002), Ground cover systems (Shan *et al.,* 2002), System of Rice Intensification (SRI, Stoop *et al.,* 2002), Aerobic rice (Bouman *et al.,* 2002), Raised beds (Singh *et al.,* 2002) and Growing rice under sprinkler and drip irrigation system. These technologies helped farmers to save time, labour, cost and water for irrigation.

3. Emerging Challenges

To improve productivity of rice using conventional breeding is the most difficult task now due to narrow genetic base, less variability in the traits, dynamic nature of biotic and abiotice stresses, poor financial resources and support, changing climatic scenario and more labor oriented. While proving the fountain head of genetic variability, the hybridization strategy has enabled breeders recombine traits of interest leading to hundreds of varieties suitable for different rice ecologies, defending biotic stresses and meeting consumer quality preferences. The strategy however failed to raise the genetic yield level beyond another 15%. Plant breeders, agronomists and physiologists at IRRI in the late 1980s postulated that the plant type of *indica* HYVs varieties may limit the further improvement in their yield potential. Yield potential need to be improved by 25-30% to meet the future demand. *Per se* yield stagnation in varieties and hybrids. Genetic diversity in key traits of yield is limiting in cultivated species. More than 95% of semi dwarf varieties have *sd1* gene. 95% of hybrid rice have WA as CMS source. Disease and insect pest scenario is changing. The virulence pattern of pathogen and insects is changing. Abiotic stresses, drought, heat and salt are the major future concerns.

4. Future Demand Projections and Prospects of Their Achievability

Based on the trend of consumption, the requirement of rice will be 130 and 190 million tonnes by 2025 and 2050. Meeting the demand projection by 2025 though difficult not unachievable given the underexploited potential of the currently available varietal technologies and scope for extensive adoption of hybrid technology. Achievability of the projection beyond 2025, would not be possible through the currently available crop improvement approaches warrenting innovations in breeding selection strategies.

5. Challenges of Abiotic Stresses

Over half the world's rice area is affected by drought, flooding, salinity, nutritional deficiencies and toxicities. Most of the world's poor rice farmers live in these areas at high population densities. Future needs have to be met from these marginal lands; since productive areas are exhausted. Addressing abiotic constraints facing today's farmers will prepare us for future needs and climate change challenges. Rice gene pool provides a rich source of traits for tolerance of most abiotic stresses, including salinity, drought and submergence. Unlike most cereals, major QTLs/genes identified; can be combined to attain sufficient tolerance at field level, and for multiple stresses.

6. Depleting Genetic Diversity

Not more than 15% of the diversity has been utilized in rice breeding. In tropical Asia, 95% of High Yielding Variety (HYV) have been developed based on a single dwarfing gene Sd1. In Bangladesh, 62% descended from common stock. In Indonesia,74% descended from common stock and > 50% of rice area under three varieties. In Thailand, 50% area under two varieties. Narrow genetic variability of commercial cultivars in Brazil (Montablan *et al.,* 1998), India (Mishra, 2002), USA (Dilday, 1990) and Japan (Kaneda, 1985) have also been reported. Now there is a trend of more inter crossing of improved cultivars; thus more depletion of genetic diversity have been seen. This is what we followed.

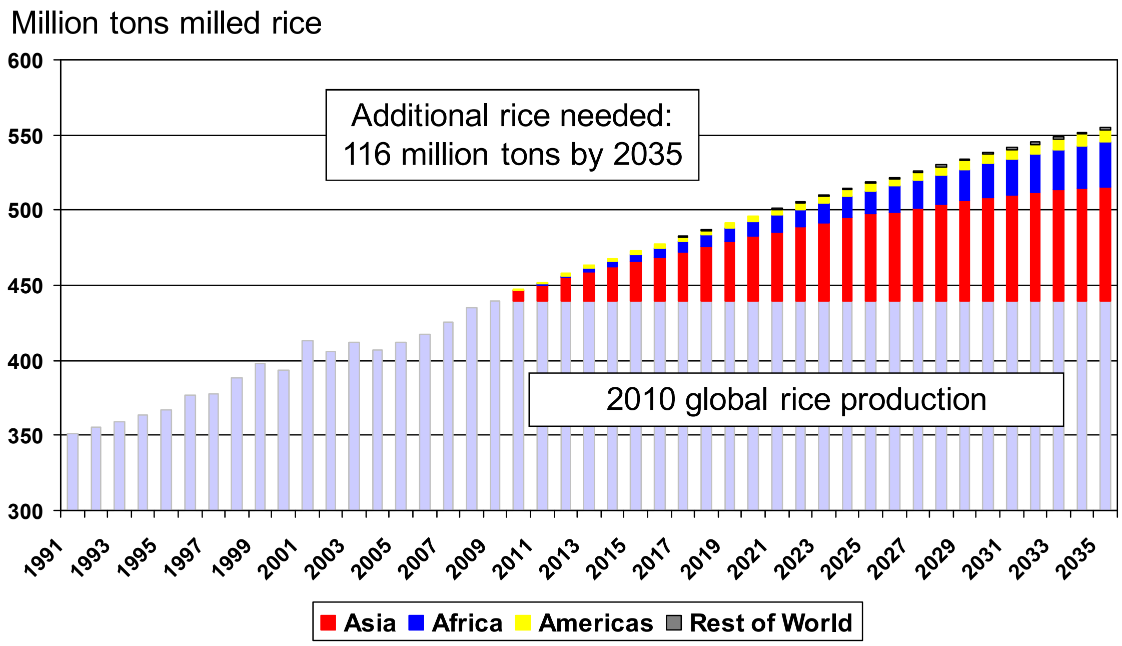

Fig. 4. Rice Outlook (Source IRRI; GRiSP (2010).

7. Constraints to Achieving Future Demands

- Plateuing of yield level of irrigated rice.
- Large area under rainfed rice (>55%) with very low and inconsistent productivity.
- Shrinking favourable growth factors of the 1970s (water, soil health, genetic variability).
- Decreasing input use efficiency.
- Adverse impact of climate change.
- Continued reservation against GM varieties.
- Growing labor and energy shortages.
- Adverse cost-risk-return structure of farming.
- Reluctance of youth to take to farming.

8. Reasons for the Slow Pace of Adoption of Hybrid Rice in Developing Countries

- Yield advantage not to the expected level of farmers.
- Inconsistent yield performance.
- Lack of hybrids of medium and medium late maturity needed for the largest (*Kharif*) area.
- Consumer quality far below the acceptable level.
- Susceptibility to diseases and insect pests.

9. Future Needs

Under adverse circumstances of reducing land, labor, water availability and increasing threat of climate related changes, now it is time to generate genetic variability, increase yield potential, develop better climate adapted varieties like aerobic rice, dry direct seeded rice, by combining traits/QTLs/genes through marker assisted breeding, target both maintenance and forward breeding. Also develop new technologies that raise the yield in low potential areas. To improve yield further we need to improve both source and sink. For 15t/ha yield, we have to have 30t/ha biomass which may be difficult with present day semi dwarf varieties having *sd1*. Biomass can be increased by improving photosynthetic efficiency along with storage capacity for reserve carbohydrates. For which relevant variation within the cultivated germplasm is inadequate. Between species also variation need to be utilized extensively. Exploration of inter specific and sub specific variability is important to improve physiological efficiency, to improve total biomass per unit height of plant. The novel genes and donors for biotic abiotic stresses tolerance needs to identified and introgressed. Most of the genes for biotic stress resistance from wild species have broad spectrum resistance.

10. Strategies for Enhancement of Yield Advantage of Hybrid Rice

Shift in breeding emphasis from intra subspecific (*indica/indica*) to inter subspecific (*indica/japonica*) hybrids (Super hybrids Tian you perjiu, Ei you 9308 etc) and overcoming inter-subspecific hybrid sterility by use of wide compatibility system accessed from Dular, Keta Nangka etc is needed. Equal emphasis given to PGMS and TGMS based 2-line breeding using sources like NangKhen 58S, Annong S1, Norin 12, SA2 and F61.C4 genes from maize have been successfully cloned and efforts are underway in China to transfer C4 gene into parental lines of super rice to further increase the yield potential by a big margin. The current hybrids give 15-25% higher yield than HYV. The yield ceiling of rice hybrids can further be raised through new technologies. Hybrids are more efficient in per day grain production. Hybrids for different ecological situations and duration groups are now available or are in pipeline. The current weaknesses of hybrids can be taken care of by improving the parental lines and choosing the right parents for grain quality and milling recovery issues. Hybrids are capable of performing good even under short period of water stress and for better N uptake capability.

11. New Plant Type: Basis of Conceptualization and Prospectus

Conceptually it is tailoring of plant type ideally adapted to high density planting (Harmonious marriage between genotype and crop geometry) that would help increase biomass and thereby grain yield (Eg. Maize and major millites).

12. Green Super Rice: Breeding Strategy for Genomewide Pooling of Synergistic Yield Genes

Basically a massive breeding effort are going placing emphasis on development of ecologically and economically sustainable varieties/hybrids in higher yield backgrounds. The breeding strategy aims at pooling of complex trait specific non allelic QTLs of promise derived from different cultivar donor sources into country/region specific popular varieties. Recovery of promising lines from such multiparent crossing programme is attributable to harmonious complementation of genetic networks for complex traits which otherwise are incomplete in both the parents.

13. Identification and Exploitation of Still Unfolded Yield Genes

Recent studies using molecular techniques suggest that only a small fraction (<15%) of the genetic variability has been captured in the development of cultivars. Sizeable allelic variations of genes governing economic traits especially yield have been lost in domestication process and subsequent development of improved varieties by human selection. Thus a very large genetic variability is still available in crop gene pools to be identified and used.

14. Plant Architecture in Rice

Plant architecture is determined mainly by plant height, culm strength, tiller number, leaf orientation and panicle morphology. Plant architecture is unique to varietal groups in rice and genotypes of Ideal Plant Architecture (IPA) yield the highest (Eg: T(N)1 – *indica*; shaoniejing – *japonica*; I/J combinations). Very little is known of genetics and breeding behaviour of ideal plant architecture.

15. Manipulation of ADP Glucose Pyrophorylase for Yield Enhancement

Potential of the enzyme was demonstrated by silencing the gene that drastically reduces its activity and starch accumulation (Lin *et al.,* 1998). Engineering potato with the gene *gl gc,* a mutated form of ADPGPPase from *E.coli* that enhanced starch yield (Lark *et al.,* 1992). Wide variability in the enzyme activity and starch accumulation in rice germplasm (Devi *et al.,* 2010) is documented.

16. C4-Re-Engineering Photosynthesis to Develop Physiologically Efficient Rice

C4 rice could increase yield by 50% with double water use efficiency and improve nitrogen use efficiency.C4 photosynthesis is one of the few evolutionary mechanisms that could deliver these superior combination of benefits.

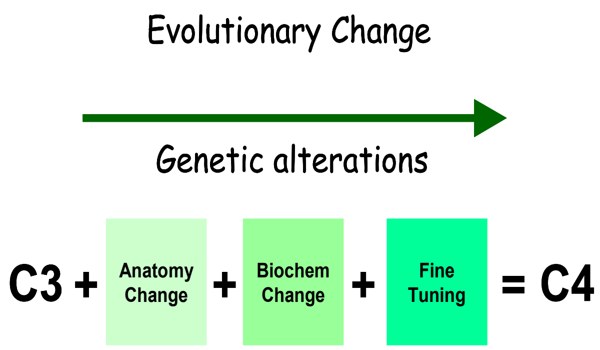

Fig. 5. Schematic diagram of conversion of C3 into C4 (Source:P. Quick & J. Sheehy, IRRI)

17. Modifying Rice Breeding Program

Plant Breeding is the art and science of improving the genetic architecture of the plants. Earlier, plant breeder's art and skill was totally used for varietal selection but now both science and art are being used for breeding purposes.

Breeders (increase) | science (increase)

Breeding procedure	% Art	% Science
Domestication	100	0
Pure line selection breeding	80	20
Controlled mating breeding	50	50
Ideotype breeding	45	55
Population breeding	40	60
Marker assisted breeding	30	70
Genomic selection breeding	20	80

Fig. 6. Plant Breeder's working strategy.

18. Conclusion

Global rice demand is estimated to be 852 million tons in 2035. This is an overall increase of 176 million tons in the next 20 years. Potent technologies like "Hybrid Rice" offer great opportunities to increase productivity/unit area to mitigate such challenges. Now its time to change breeding strategies. Breeders need to align, learn and apply the new technology in their breeding program. Breeders need to make sure that using diverse alleles will be one of the important component of their breeding program. Breeders need to be given opportunity by management. To meet future challenges, major strategy to improve yield potential includes recombination breeding, ideotype breeding, hybrid breeding, exploitation of wild species and germplasm, enhancement of photosynthesis, genomic approaches and physiological approaches. The strategy followed for improving yield potential are widening the genetic base of rice by incorporating traits from tropical *japonica*, improving the source and sink and redesigning plant type, improving the photosynthetic efficiency by introgressing trait from wild rice, improving multiple traits of biotic and abiotic stresses tolerance using MAS, identifying and introgressing novel genes for biotic stresses tolerance, multi location evaluation and selection in BC1F3, three way F3 and back cross intermated populations derived from *indica*/Tropical *japonica* crosses. Despite the progress made we have several miles to go.

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