Biofortification: A Global Challenge Program

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A Global Challenge Program on Biofortification with proposed funding of US$90 million over 10 years has just been approved by the Consultative Group on International Agricultural Research (CGIAR). Program researchers in collaborating agricultural and public health (nutrition) disciplines will apply food systems strategies to deliver more nutritious staple crops to resource-poor consumers. Improved grain will be richer in iron, zinc, vitamin A, selenium, and iodine, as needed.

Introduction

This paper is a personal view of how the philosophy and strategy for the Biofortification Challenge Program will develop in rice to achieve its objectives. Full funding of the Program is as yet incomplete and a program leader for it has only just been advertised (March 2003).

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A team of plant breeders, agronomists, chemists, human nutritionists, social scientists, and others will develop the Global Challenge Program (GCP) on Biofortification into a US$90 million international effort to redress nutritional poverty as a result of approval given to the proposal by the CGIAR-Annual General Meeting in Manila, Philippines, in October 2002. Nine CGIAR centers are involved, along with designated national agricultural research and extension systems (NARES) and universities in both developing and developed countries. The rice subprogram will draw on more than $700,000 annually to support the effort to improve the nutritional value of rice, especially for iron, zinc, vitamin A, calcium, iodine, and selenium—all being nutrients especially low in rice and widely deficient in resource-poor, rice-consuming communities. The research involves feeding trials in humans both in controlled conditions and in free-living, village-based comparisons, capacity building, farmer participatory research, agronomic extension work, as well as the core rice breeding and biotechnology work for which IRRI is well known. The effort will be the largest yet to proceed within the new conceptual framework of the productive, sustainable, and nutritious food systems paradigm for agriculture and public health.

Overview of the proposal

A new paradigm for agriculture in the 21st century was proposed (Welch and Graham 2000) that views agriculture as an instrument for public health and focuses attention on the role of agriculture in delivering nutrients to humans and animals in balanced amounts that can sustain maximal physical and mental activity of the humans who are simultaneously the drivers of the food system and its dependents. This is known as the productive, sustainable, and nutritious food systems paradigm for agriculture and public health.

The GCP in Biofortification seeks to apply the food systems approach to research within the crop-based CG centers responsible for staple crop improvement, including IRRI and its NARES and advanced research institution (ARI) partners. In all, the GCP in Biofortification will support research and development of nutrient-dense cultivars of 17 crops, 6 Phase 1 crops, and 11 Phase 2 crops. The six Phase 1 crops—rice, wheat, maize, beans, cassava, and sweet potato—have already completed an exploration of the germplasm and initial studies of the genetics and genotype by environment (G × E) interactions, and are therefore poised to take advantage of a major input of resources. Phase 2 crops are about to begin primary germplasm screening

and will have less funding in the first 4 years: these crops include peanut, lentil, cowpea, pigeon pea, sorghum, millet, barley, banana, plantain, potato, and yam. Funding will support capacity building and farmer participatory research with NARES partners and will be allocated also for partner research in biotechnology, studies of bioavailability, strategic initiatives, economics and social marketing, not to mention administration and communications.

Progress in rice

Analysis of rice lines in the IRRI germplasm bank was begun in 1994 by Dr. D. Senadhira with the aid of modest exploratory funding by the Danish International Development Agency (DANIDA) and the United States Agency for International Development (USAID). Since then, some 12,000 entries have been analyzed for essential minerals by ICP spectrometer at the Waite Analytical Services of the University of Adelaide. Because of significant site and season effects, all materials to be compared were grown together with reference lines at the same site and the daughter seed so obtained was sent for analysis. This laborious process eliminates effects of seed nutrient content caused by varying mother-plant environment. A summary of the first broadly based survey of rice germplasm carried out in this way is shown in Table 1 (Gregorio et al 2000).

Improved cultivars with exceptionally high iron or zinc concentration were not found in this series of screening, but several aromatic rice varieties were found among the high-iron varieties. A series of seven comparisons of aromatic and nonaromatic varieties was made: two sets typical of the studies at the seven locations on the station (Graham et al 1999) are shown in Table 2. In a subsequent study of a doubled-haploid population (Azucena / IR64), the linkage between aromaticity and high iron density was shown to be quite weak, only one of four quantitative trait loci (QTLs) for high iron being located on the same chromosome arm as the aroma locus and at some distance from it (Gregorio et al 2000).

Several tests have been conducted to examine the effect of soil and climatic factors on the iron and zinc concentrations in grain (G × E). In one, four varieties were grown on normal and saline soils in a coastal area in Pili, Iloilo, Philippines, in the 1992 wet season and their harvest was analyzed for iron and zinc in grain. In salt-sensitive IR29, grain iron increased under saline soil conditions and, in tolerant varieties (IR74, IR9884, and Pokkali), there appeared to be a reduction in iron concentration, though slight. Independently of tolerance for salinity, zinc concentrations of these lines decreased as the salinity increased. At the time of the planting experiment on the IRRI farm in the 1994 dry season, the differences observed were not significant for iron concentration but were slightly and significantly so ($P<0.01$) for higher zinc concentrations in grain from earlier planting (Graham et al 1999). The biggest effect, seen in several experiments, was a higher iron concentration with increasing nitrogen fertilizer application. As expected, though this has not been subjected to formal experimentation, iron concentrations tend to be lower in upland conditions (G. Gregorio, IRRI, pers. commun.).

Table 1. Iron and zinc concentrations in brown rice varieties grown under similar growing conditions in six sets at IRRI, Los Baños, Philippines.

Variety set	Samples (no.)	Fe (mg kg^{-1}) Mean ± SE (range)	Zn (mg kg^{-1}) Mean ± SE (range)
Traditional and improved varieties	59	13.0 ± 2.6 (9.1–22.6)	24.0 ± 4.7 (13.5–41.6)
IR breeding lines	350	10.7 ± 1.6 (7.5–16.8)	25.0 ± 7.6 (15.9–58.4)
Traditional and improved varieties	63	12.9 ± 3.1 (7.8–24.4)	24.4 ± 4.7 (16.5–37.7)
Tropical japonicas	250	12.9 ± 1.5 (8.7–16.5)	26.3 ± 3.8 (17.1–40-1)
Popular varieties and donors	199	13.0 ± 2.5 (7.7–19.2)	25.7 ± 4.6 (15.3–37.3)
Traditional and improved varieties	18	13.8 ± 2.3 (10.8–18.0)	24.2 ± 4.1 (19.9–33.3)

Table 2. Elevated concentrations (mg kg^{-1}) of iron and zinc in aromatic rice varieties in comparison with nonaromatic types grown at IRRI, Los Baños, in 1996 (Gregorio et al 2000).

Aromatic line	Fe	Zn	Nonaromatic line	Fe	Zn
Set 1					
Basmati 370	16.3	34.4	IR8	12.3	17.3
Gaok	16.0	26.4	IR36	11.8	23.1
Azucena	18.2	29.3	IR74	11.2	24.0
Set 5					
Ganje Roozy	18.1	36.6	Bg 379-2	11.3	20.5
Banjaiman	18.1	33.3	BG1370	11.5	19.5
CT 7127	17.1	32.4	UPLRi 7	10.8	20.9
Lagrue	19.0	34.8	Tetep	10.7	24.1

is the obvious location for a critical mass of scientists in grain quality; micro-nutritional quality; nutrition science; organic, micronutrient, and analytical chemistry; biochemistry; and grain processing. This core of specialties will not only support the breeders and agronomists involved in improving rice nutritional quality—and researching more efficient ways of doing so—but will also be the focus of capacity building in NARES and the conduit for the flow of knowledge from their colleagues in ARIs to other IRRI staff leading the effort in agronomy and plant breeding. Finally, these researchers will be involved in developing new products that contribute to better nutrition. Research on milling efficiency will be critical to the outcomes of this GCP.

In tests on rats and human cell cultures, the extra iron in high-iron lines is bioavailable (Welch et al 2000). Therefore, based on the apparent link between high iron and aroma, advanced lines of Dr. Senadhira's cross of a traditional aromatic rice with a high-yielding modern variety (Zawa Bonday/IR72) were analyzed for minerals. Three high-yielding lines with high iron and zinc concentrations, good disease resistance, and good cooking quality were identified. One of these, IR68144B-2-3, was multiplied for bioavailability studies in humans. A preliminary feeding trial with mildly anemic women was conducted to determine the logistics for a larger feeding trial that is currently under way with nearly 300 participants. A local market rice, C4, is being used as a low-iron control, and such is the quality of the two rice lines that they are consumed in almost equal amounts. The trial is a double-blinded study such that neither the subjects nor the experimenters know the key to the treatment assignations. This trial is now being wound up and data assessment is under way.

Evolving a plan for biofortification research at IRRI

As milled rice has the lowest iron concentration of any known staple crop yet is the major food source for nearly half of the world's population, it is essential that a major thrust of the Bioforti-fication GCP be in improving the nutritive value of rice. IRRI

Accordingly, a new Center for Grain Quality and Nutrition Research at IRRI to be the focal point of the GCP and its outreach to rice-growing countries is under development. It is proposed that it be staffed by three or four internationally recruited scientists in the abovementioned disciplinary areas and have a lead scientist drawn from among the senior staff. The center ideally will also take responsibility for the existing grain quality laboratory (to be upgraded substantially) and a new plant micronutrient laboratory that will analyze grain produced by the breeding and agronomic research efforts. Both laboratories will be equipped with advanced quality assurance procedures. They will have service, research, and capacity-building roles.

It is intended that all rice-breeding programs will adopt nutritional and cooking quality objectives, using the additional resources available in the GCP. Faster and cheaper methods of analysis of grain for iron, zinc, and carotenoids are needed and will be researched by the team. The overall objective is to incorporate these new traits in the highest-yielding material so that its impact in the marketplace is assured because farmers will want to grow it for the yield advantage. This is especially important in an unsophisticated market that will not pay extra for better nutritional value. At the same time, because of the synergy between these micronutrients in enhancing the absorption and function of each other (Graham et al 2000), a parallel strategy will be to incorporate high-iron, high-zinc, and golden rice traits in that one variety. Such a variety will help overcome not only single deficiencies of iron, zinc, or vitamin A but also multiple deficiencies of them and do so more efficiently so that modest expression of each trait (and therefore fewer genetic loci involved), rather than maximal expression, may be adequate to solve the problem. This strategy also has the advantage of having an identifiable product (being yellow) in the marketplace, and this can be promoted as being healthy for infants, children, and pregnant and lactating women.

A particular opportunity exists for agronomic research and extension within the GCP. Of the five most prevalent micronutrient deficiencies (iron, zinc, vitamin A, selenium, and iodine—affecting 4–5 billion people [WHO 2002]), only three can be addressed by fertilizer increasing the concentration in the grain: zinc, selenium, and iodine (Graham et al 2001); the other two, iron and vitamin A (β-carotene), can only be meaningfully improved by plant breeding/biotechnology. Generally speaking, higher concentrations in grain can be achieved by fertilization than by plant breeding but the problem is that, for selenium and iodine, there is no yield incentive to encourage farmers to use fertilizer. This could be achieved by legislation to require fertilizer companies to coat urea for rice production with traces of these two ultra-micronutrients, or by treating irrigation water in the main irrigation channels wherever this approach would work. Delivery of these potentially toxic but essential ultra-micronutrients through the food system is the safest way to do so, eliminating the possibility of toxicity, while at the same time ensuring their widest distribution. Demonstration of efficacy in all situations is needed. In the case of zinc, there is a yield advantage in half of all soils, and probably more than half in the case of rice because of its inherent sensitivity to this deficiency. The high-zinc seeds, moreover, are more nutritious not only to humans but to the next generation of seedlings, which become more vigorous and better able to withstand weed competition, pathogen and pest attack (including suppression of motility and symptom expression in viral diseases), and other stresses, including salinity, since zinc controls membrane permeability.

Future strategies

Functional genomics is likely to increase greatly the efficiency by which breeders can optimize this program. At the same time, further research into gut physiology will probably create new opportunities. A current example is the prebiotic polysaccharides, fructans. The human gut does not have the enzymes to cleave these chains into absorbable sugars so they reach the colon intact where bifidobacteria, present in small numbers normally, can use fructans as an energy source, can multiply, and, by a variety of effects, can increase the absorption of iron, zinc, and calcium from the colon. As these fructans also contribute to stress tolerance in the vegetative plant, there may be opportunities to explore a potential win-win situation. Another factor in the future is the likely full recognition of phytate as an essential nutrient and the establishment of minimum requirements in the diet for its various functions, including prevention of cancers, especially colon cancer. The improved efficiency of genetic transformation technology is likely to contribute faster, safer, and more effective ways to improve the nutritional value of rice.

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