Cereal biofortification: strategies, challenges and benefits

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Bulleted Points

Thirteen million children under the age of five years have severe acute malnutrition and in sub-Saharan Africa 9% of children have moderate acute malnutrition

Several major projects are well advanced to biofortify cereal staples including maize, rice, pearl millet and sorghum, with the objective of combatting micronutrient malnutrition in developing countries

Biofortifed cereals have great potential, in particular to prevent Vitamin A deficiency in young children but successful biofortification projects require a major collaborative effort involving all players

Under-nutrition is seen as one of the key underlying causes of the 10 million child deaths each year, most of which are from preventable causes and most of which occur in poor countries (4). Worldwide, 13 million children under the age of five years have severe acute malnutrition and in sub-Saharan Africa 9% of children have moderate acute malnutrition (7).

The major direct causes of under-nutrition in poor developing countries are insufficient food intake and an unbalanced diet caused by lack of variety of different foods, coupled with the outbreak of diseases (23). Unbalanced diets are often deficient in micronutrient-rich foods and may also have low bioavailability of essential micronutrients (7). Plant foods are the most important part of the diet in most developing countries (27). However, plant foods, especially cereals, are not always reliable in providing a nutritionally adequate diet (11). Cereals are generally a source of poor quality protein and often micronutrients such as iron, zinc, iodine and Vitamin A are present in low levels, or are not readily bioavailable.

Malnutrition Alleviation Strategies

To address micronutrient deficiencies, various malnutrition alleviation strategies have been employed, including fortification, supplementation, nutrition education, dietary diversification and more recently biofortification (7). Fortification is the addition of one or more essential nutrients to foods, usually commercially produced, such as maize meal fortified with Vitamin A, iron and zinc as is the case in for example South Africa, in order to prevent or correct a known deficiency. Supplementation is the distribution of nutrient supplements or clinically administered doses of vitamins and or minerals to groups of individuals at risk of specific nutrient deficiencies. It can be effective, but is usually short term and the strategy needs the presence of an effective health infrastructure. In Burkina Faso, for example, Vitamin A capsules (retinol palmitate) (6) and zinc (zinc gluconate) (17) are distributed to families with cases of xerophthalmia. Nutrition education is usually combined with attempts at dietary diversification and aims to improve individuals eating habits. These interventions can be linked to garden projects, where support is given to grow crops which can help alleviate dietary deficiencies (7).

Biofortification aims to either increase the density of nutrients in staple crops and/or increase their bioavailability by conventional plant breeding or by use of transgenic techniques, or indeed by a combination of the two (30). It is directed towards improving the nutritional status of the rural poor, who have little dietary diversity, little or no access to commercially produced and marketed fortified foods and only sporadic exposure to nutrient supplements. Biofortification of these people's staple foods should ensure a continual supply of foods with improved nutrient content. Biofortification is a term used in a broad sense to include improving oil profiles, amino acid profiles and improved protein quality and quantity of specific crops, or in a more narrow sense when micronutrients such as provitamin A, iron and zinc are targeted (2). Although biofortifcation is usually considered as a relatively new strategy to alleviate malnutrition, its history goes back some 50 years. In 1964, Mertz et al. (19) published the first paper describing the high lysine content of the opaque-2 (o2) maize mutant and thus introduced the concept of the production of cereals with high nutritional value. The opaque -2 maize line was the precursor of Quality Protein Maize (QPM). Soon after, in the 1970s, high lysine sorghum, P721Q was obtained by chemical mutagenesis of a normal, non-tannin line, P-721N (7). More recently, sorghum lines derived from P721Q have been shown to have some 10-15% higher uncooked and approximately 25% higher cooked in vitro protein digestibility than P721N (8).

Biofortification is believed to be cost effective because after the initial, if considerable investment to produce seeds with increased nutritional content and bioavailability, recurrent costs are relatively low and the delivery of increased nutrients is sustainable (5, 22). There does seem to be some additional advantages to the farmer when the biofortification of minerals are considered. According to Nestle et al. (22), seeds with improved mineral profiles are more resistant to disease and environmental stresses, more seedlings survive and initial growth is more rapid. This results in higher crop yields. Higher crop yields could address the major cause of under-nutrition in developing countries which is insufficient food.

Challenges

Biofortification does have challenges in addition to the high initial costs of development, which has already been referred to (5, 22). It is essential that the target breeding level for the different nutrients must be determined in advance. This is a complex process and involves the determination of the adoption level by the farmers, the quantity of food products made from the crop consumed, the post-harvest and preparation and cooking losses and the bioavailability of the nutrients and the nutrient requirements. Thus, target breeding levels must ensure that there is a sufficient impact on the nutritional status of the intended recipients.

It also takes a considerable time, up to a decade, before biofortified crops are released and become widely available (5). If crops are biofortified by genetic transformation then there are additional political and regulatory issues to be addressed (3). Lastly and probably most important of all, farmers must be persuaded to grow the improved crops and consumers must find food products made from biofortified crops acceptable. To ensure all these factors come together a multi-disciplinary approach must be used involving plant breeders, geneticists, agronomists, extension officers, food scientist, nutritionists, social scientists, economists, market and product developers and educators. The complexity of the process of development and acceptance of biofortified crops should not be underestimated.

Today, worldwide there are several major biofortification projects on-going and to date biofortification of several staple cereal crops with a number of different nutrients has met with some success. Quality Protein Maize has improved protein quality through increased levels of lysine

(50%) and tryptophan (29) and has been shown to have positive effects on the nutritional status of children in the Ethiopian highlands (2). Golden Rice has elevated levels of β-carotene (35 μg β-carotene per g dry rice) (Fig. 1) as a result of genetic modification (GM) technology. The β-carotene is effectively converted to Vitamin A in humans (26). Confined field trials for Golden Rice have been undertaken in the Philippines (16). Currently, further development work is being undertaken to biofortify Golden Rice with iron, zinc, high quality protein and Vitamin E (ProVitaMinRice) (12). Provitamin A maize (15 μg β-carotene per g dry maize) , also with enhanced levels of β-carotene but produced by non GM technology, is being developed by the HarvestPlus organization in collaboration with the International Maize and Wheat Improvement Center (CIMMYT) and the International Institute for Tropical Agriculture (IITA) (5). It is to be released in Zambia in 2012. HarvestPlus, in collaboration with the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), is also releasing pearl millet varieties biofortified with iron (64% increase) in India in 2012, and later in Mali and Niger in Africa (5). The Africa Biofortified Sorghum (ABS) (1) project, led by the Africa Harvest Biotechnology Foundation International based in Kenya, is developing a biofortified sorghum by GM technology, specifically for use by farmers in Africa. ABS is intended to have increased levels of essential amino acids especially lysine (80-100% increase), improved protein digestibility, and increased Vitamin A (20 μg β-carotene per g dry sorghum), Vitamin E, iron (50% increase) and zinc (35% increase) (15). Figure 2 shows food products made from prototype ABS compared to those from normal sorghum. ABS sorghums are currently undergoing field trials.

<FIGURES 1 AND 2 NEAR HERE>

As part of the ABS project, we investigated the potential impact of biofortification of the above described differently biofortified cereals on the nutritional status of young children, aged 2-5, using Burkina Faso as a rural African example. Burkina Faso which has high rates of chronic (39%) and acute (19%) malnutrition and in 2009 was ranked 11 in the world in terms of under-five mortality rate by UNICEF (28). The latter is a critical indicator of child well-being. Burkina Faso has a population of 15.2 M and an annual cereal production of 4.3 M tonnes (9). Sorghum (42%), maize (25%) and pearl millet (27%) make up 94% of the cereal production (10) and are the major staples of the rural poor (18). Improvement of agriculture is a major priority and of significance with regard to biofortified cereals, Burkina Faso has legislation in place for the cultivation of GM crops (3).

By far the major food group consumed by the children was cereals, making up some 96.5% by weight of the 2-3 year old and 97.5% of the 4-5 year-old's diet. Thus, all other food groups combined contributed only 3.5% (2-3 year-old) and 2.5% (4-5 year-old) to the diet, respectively. Table 1 shows the relative amounts of each cereal consumed. Maize was the predominant cereal eaten (79-87% of cereals consumed), followed by much smaller amounts of sorghum, rice and pearl millet. Wheat, eaten in the form of white bread, was consumed rarely and made up only 0.3% of all the children's cereal intake. The amount of sorghum consumed was surprisingly low as the survey area, is one of the major sorghum growing areas of Burkina Faso. Through focus group discussions, it was found that the sorghum was used grown primarily for sale, for the production of the local beer.

Over 70% of the children were energy deficient when compared to their RDA. This is primarily due to maize tô, the main food in the diet, being low in energy (234 kJ/100 g), due to its high moisture content (88%). Fifteen percent of 2-3 year olds and 10% of the 4-5 year olds were protein deficient. Further, the quality of the protein was low, as much of it came from maize.

Lack of dietary diversity was also noted by Nana et al. (21) and Sawadogo et al (24) during food consumption surveys in other parts of Burkina Faso. The majority of the diet consisted of different porridges. Soured maize tô, a gel-like porridge made from refined maize meal (Fig. 3) was the most predominant dish eaten. This was followed by sour maize gruel, sorghum or pearl millet tô and rice. Legumes were consumed as cowpeas and only when seasonally available (November and December), because of storage losses due to bruchids (20).

<FIGURE 3 NEAR HERE>

Potential improvements in the children's nutritional status were calculated based on the assumption that the proportion of each of the major cereals consumed was replaced with biofortified grain, i.e. maize replaced with QPM maize or Provitamin A maize, sorghum with ABS sorghum, and pearl millet with iron biofortified pearl millet and rice with Golden Rice. The nutrients considered were lysine, vitamin A, iron and zinc. The amount of the nutrient from other sources was then added to the value from the biofortified cereals to give the new total intake of each nutrient. The new total intake was then compared with the RDA for each nutrient and the nutrient surplus or deficiency calculated. Food matrices have been shown to affect vitamin A bioavailability. Two conversion factors of β-carotene to retinol were used, 3.8:1 as determined by Tang et al (26) specifically for Golden Rice and 6:1 as defined by the FAO for mixed diets (8). Assumptions were made based on published data on the biofortification levels of these nutrients in the specific cereals when compared to their 'normal' equivalents' as described. This approach did not take into consideration the disease burden of the children, any potential change in bioavailability of the nutrients on biofortification or change in processing losses resultant on biofortification.

Potential Benefits

The findings indicated a strong positive effect on the children's nutrient status, in terms of lysine, vitamin A, iron and zinc, assuming that all the children's cereal intake was replaced by the current biofortified cereals in the same proportion as the cereals are currently consumed (Table 1). As maize is the predominant cereal consumed, if it were replaced by QPM maize, the lysine component of the diet would be on average be raised above the children's RDA. The effect of the replacing sorghum with ABS sorghum on lysine intake would be negligible as sorghum was such small proportion of the children's diet. In contrast if maize were replaced by Provitamin A maize, the effect on the children's vitamin A intake would be dramatic, with all the children meeting their RDA. The effect of replacing rice with Golden Rice on vitamin A intake would be much smaller as rice was only a very small proportion of diet. The impact of biofortification of the staple cereals on the other nutrients considered would be negligible as the proportions of the sorghum and pearl millet in the diet, which would be replaced by ABS sorghum and iron biofortified pearl millet, were so small.

The assumption that all the children's cereal intake would be replaced by biofortified cereals may be over-optimistic. A prediction by HarvestPlus has indicated an estimated contribution of biofortified cereals to the diet of 30-40% (14). Notwithstanding this, for example a meta-analysis of community-based studies conducted in Sub-Saharan Africa, Asia and Latin America, QPM maize showed a 12% and 9% increase in the rate of growth in weight and height respectively, of infants with mild to moderate undernutrition, when maize was the major staple (13). Also, according to Akalu et al (2), in the first published study on home cultivation and use of QPM maize in children's diets, in the western Ethiopian highlands, growth faltering could be prevented or at least reduced and in some cases may support catch up increase in weight. A comprehensive analysis by Stein, Sachdev and Qaim (25) of the potential effect of the introduction of Golden Rice to public health in India concluded that Golden Rice could more than halve the disease burden of Vitamin A deficiency in India and at the same time be cost effective (25). Additional biofortification of Golden Rice with iron, zinc, high quality protein and Vitamin E (12) as being currently researched would potentially have even greater benefits to the nutritional status of Indian people, as would the consumption of ABS sorghum biofortified with this range of nutrients, to peoples whose major staple is sorghum.

Conclusions

Sadly, our study, like others, showed that the majority of children living rural Burkina Faso are severely undernourished as a result of the low amount of food they consume and their lack of dietary diversity, and consequently their low intake of many macro- and micro-nutrients. Replacement of normal staples with biofortified crops does not *per se* affect the amount of food consumed. However, the strategy of most biofortification programs is to put the traits for biofortification into the most profitable and highest yielding varieties available (5), which would then to some extent address the issue of insufficient food availability. For biofortified cereals to make a broad impact on the nutritional status of such children in rural Africa, ideally the predominant cereals consumed should have enhanced levels of multiple critical nutrients, as with Africa Biofortified Sorghum and the improved 'ProVitaMinRice' Golden Rice.

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LEGENDS TO FIGURES

Figure 1. Golden Rice grain compared to white rice grain in a screenhouse of Golden Rice plants. Photograph from the International Rice Research Institute via Wikimedia Commons

Figure 2. Food products made from prototype Africa Biofortified Sorghum compared to those made from normal sorghum

Figure 3. Making maize tô in Dossi village, Burkino Faso

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Table 1: Potential effect of replacing the cereal portion of children's diet with biofortified cereals on the intake of certain nutrients of 2-3 and 4-5 year olds in Burkina Faso.

2-3 year olds

					ABS Sorghum	**Provit. A Maize**	**QPM Maize**	**Golden Rice**	**Iron Pearl millet**	**Wheat**
Percentage each cereal consumed					**4.56**	**87.15**	**87.15**	**4.04**	**3.94**	**0.31**
Nutrient	**RDA***		**Total intake**	**Intake from cereal**						
Lysine (g)	64 mg/kg body wt (0.72 g)	Normal	0.60	0.40	0.02	0.35	0.35	0.02	0.02	0.00
		With BF	0.81	0.61	0.04	NBF	0.53	NBF	NBF	NBF
Vitamin A (µg RE)	Safe Limit 400 µg RE	Normal	4.9	0.7	0.03	0.61	0.61	0.03	0.03	0.0
		With BF	29.7 (ABS)	25.5 (ABS)	24.8[8]	NBF	NBF	NBF	NBF	NBF
			65.5 (GR)	61.3 (GR)	NBF	NBF	NBF	60.6[26]	NBF	NBF
			359.2 (PVA)	355.0 (PVA)	NBF	354.9[8]	NBF	NBF	NBF	NBF
			444.5 (ABS+GR+PVA)	440.3 (ABS+GR+PVA)	24.8[8]	354.9[8]	NBF	60.6[26]	NBF	NBF
Iron (mg)	11.6 mg	Normal	2.60	2.27	0.10	1.98	1.98	0.09	0.09	0.01
		With BF	2.71	2.38	0.15	NBF	NBF	NBF	0.15	NBF
Zinc (mg)	459 µg/kg body wt (5.14 mg)	Normal	2.80	2.61	0.12	2.27	2.27	0.11	0.10	0.01
		With BF	2.84	2.65	0.16	NBF	NBF	NBF	NBF	NBF

4-5 year olds

					ABS Sorghum	**Provit. A Maize**	**QPM Maize**	**Golden Rice**	**Iron Pearl millet**	**Wheat**
Percentage each cereal consumed					**9.03**	**79.28**	**79.28**	**7.38**	**4.00**	**0.31**
Nutrient	**RDA***		**Total intake**	**Intake from cereal**						
Lysine (g)	64 mg/kg body wt (0.82 g)	Normal	0.90	0.69	0.06	0.55	0.55	0.05	0.03	0.00
		With BF	1.24	1.03	0.12	NBF	0.83	NBF	NBF	NBF
Vitamin A (µg RE)	Safe Limit 450 µg RE	Normal	5.70	0.80	0.07	0.64	0.64	0.06	0.03	0.00
		With BF	77.6 (ABS)	72.7 (ABS)	72.0[8]	NBF	NBF	NBF	NBF	NBF
			168.4 (GR)	163.5 (GR)	NBF	NBF	NBF	162.8[26]	NBF	NBF
			479.7 (PVA)	474.8 (PVA)	NBF	474.7[8]	NBF	NBF	NBF	NBF
			714.4 (ABS+GR+PVA)	709.5 (ABS+GR+PVA)	72.0[8]	474.7[8]	NBF	162.8[26]	NBF	NBF
Iron (mg)	12.6 mg	Normal	4.70	4.30	0.39	3.41	3.41	0.32	0.17	0.01
		With BF	5.01	4.61	0.59	NBF	NBF	NBF	0.28	NBF
Zinc (mg)	380 µg/kg body wt (4.86 mg)	Normal	4.80	4.50	0.41	3.57	3.57	0.33	0.18	0.01
		With BF	4.94	4.64	0.55	NBF	NBF	NBF	NBF	NBF

BF-Biofortification
NBF-No biofortification
ABS- ABS sorghum
GR-Golden Rice
QPM – With QPM maize
PVA – With Provitamin A maize
RDA*- Values taken from FAO/WHO (8)
RE-Retinol Equivalent
Storage and processing losses excluded
Total nutrients from cereals and other sources
Conversion factor: Provitamin A to Vitamin A (µg RE) 6:1 (8), 3.8:1 (26)

Fig 1

Fig 2

Fig 3