Cereal Biofortification: Strategies, Challenges, and Benefits

J. Taylor and J. R. N. Taylor[1]
Institute of Food, Nutrition and Well-being and Department of Food Science, University of Pretoria
Hatfield, South Africa

F. Kini
Institut de Recherche en Sciences de la Santé (IRSS)
Ouagadougou, Burkina Faso

Under-nutrition is seen as one of the key underlying causes of the 10 million child deaths each year—most of which are preventable and most of which occur in poor countries (3). Worldwide 13 million children under the age of 5 years have severe acute malnutrition, and in Sub-Saharan Africa, 9% of children have moderate acute malnutrition (8).

The major direct causes of under-nutrition in poor developing countries are insufficient food intake and an unbalanced diet caused by lack of variety in available foods coupled with disease outbreaks (20). Unbalanced diets are often deficient in micronutrient-rich foods and may also have low bioavailability of essential micronutrients (8). Plant foods make up the majority of the diet in most developing countries (24). However, plant foods, especially cereals, do not commonly provide a nutritionally adequate diet (10). Cereals are generally a source of poor quality proteins, and micronutrients such as iron, zinc, iodine, and vitamin A are present in low levels or are not readily bioavailable.

Strategies to Alleviate Malnutrition

To address micronutrient deficiencies, various malnutrition alleviation strategies have been employed, including fortification, supplementation, nutrition education, dietary diversification, and, more recently, biofortification (8). 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 South Africa, 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 for specific nutrient deficiencies. It can be effective, but it is usually a short-term solution, and the strategy requires the presence of an effective healthcare infrastructure to be successful. In Burkina Faso, for example, vitamin A capsules (retinol palmitate) (5) and zinc (zinc gluconate) (15) are distributed to families with cases of xerophthalmia. Nutrition education is usually combined with attempts at dietary diversification and aims to improve eating habits. Such interventions may be linked to garden projects in which support is given to growing crops that can help alleviate dietary deficiencies (8).

Biofortification aims to either increase the density of nutrients in staple crops or their bioavailability through conventional plant breeding, use of transgenic techniques, or a combination of the two (28).

[1] Corresponding author. Institute of Food, Nutrition and Well-being and Department of Food Science, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa; E-mail: john.taylor@up.ac.za; Tel: +27 12 4204296; Fax: +27 12 4202839c

http://dx.doi.org/10.1094/CFW-57-4-0165

Biofortification is directed toward 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 the staple foods consumed by the rural poor can help ensure a continual supply of foods with improved nutrient content.

In a broad sense, biofortification can include the improvement of oil profiles, amino acid profiles, and the protein quality and quantity of specific crops. In a more narrow sense, biofortification can target micronutrients such as provitamin A, iron, and zinc (1). Although biofortification is usually considered a relatively new strategy for alleviating malnutrition, its history goes back some 50 years. In 1964, Mertz et al. (16) published the first paper describing the high lysine content of the *opaque-2* maize mutant, introducing the concept of the production of cereals with improved nutritional value. The *opaque-2* mutant maize line was the precursor of quality protein maize (QPM). Soon after, in the 1970s high-lysine sorghum (P721Q) was obtained through chemical mutagenesis of a normal non-tannin line (P721N) (27). More recently, sorghum lines derived from P721Q have been shown to have ≈10–15% higher uncooked and ≈25% higher cooked in vitro protein digestibility than P721N (27).

Despite the considerable initial investment cost associated with production of seeds with increased nutritional content and bioavailability, biofortification is believed to be cost-effective because its recurrent costs are relatively low and the delivery of increased nutrients is sustainable (4,19). Furthermore, there seem to be some additional advantages to the farmer when biofortification of minerals are considered. According to Nestel et al. (19), 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 also help address the major cause of under-nutrition in developing countries—insufficient food.

Biofortification Challenges

Biofortification does have challenges in addition to the high costs of development (4,19). It is essential that the target breeding level for different nutrients be determined in advance. This is a complex process and involves the determination of the adoption level by farmers, quantity of food products made from the crop consumed, postharvest and preparation and cooking losses, bioavailability of the nutrients, and nutrient requirements. Thus, target breeding levels must ensure there is a sufficient beneficial impact on the nutritional status of the intended recipients.

It can also take considerable time, up to a decade, for biofortified crops to be released and become widely available (4). If crops are biofortified through genetic transformation, there are additional political and regulatory issues to be addressed (2). Finally, and probably most important, farmers must be persuaded to grow the improved crops, and consumers must find food products made from a biofortified crop acceptable. To ensure all these factors come together a multidisciplinary approach must be used that involves plant breeders, geneticists, agronomists, extension officers, food scientists, 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, there are several major ongoing biofortification projects worldwide, and to date, biofortification of several staple cereal crops with a number of different nutrients has met with some success. QPM maize has improved protein quality through increased levels of lysine (50%) and tryptophan (26) and has been shown to have positive effects on the nutritional status of children in the Ethiopian highlands (1). As a result of genetic modification (GM), Golden Rice (Fig. 1) contains elevated levels of β-carotene (35 μg/g of dry rice), which is effectively converted to vitamin A in humans (23). Confined field trials for Golden Rice have been undertaken in the Philippines (14). In addition, further development work is being undertaken to biofortify Golden Rice with iron, zinc, high-quality protein, and vitamin E (ProVitaMinRice) (11). Provitamin A maize (15 μg of β-carotene per gram of dry maize), which also contains enhanced levels of β-carotene but is 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) (4). It is to be released in Zambia in 2012. HarvestPlus, in collaboration with the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), will also be releasing pearl millet varieties biofortified with iron (64% increase) in India in 2012,

Fig. 1. Golden Rice (background) compared with normal rice (foreground). (Photograph from the International Rice Research Institute via Yahoo! flickr.)

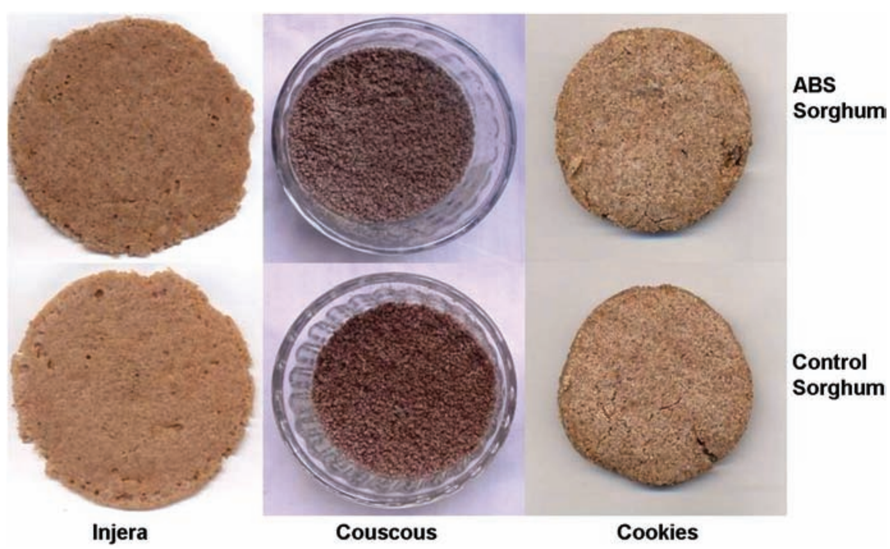

Fig. 2. Food products made from prototype Africa Biofortified Sorghum (ABS) project sorghum compared with those made from normal sorghum.

followed by its release in Mali and Niger in Africa (4). The Africa Biofortified Sorghum (ABS) project (www.supersorghum.org), led by Africa Harvest Biotechnology Foundation International based in Kenya, is developing a biofortified sorghum using GM specifically for use by farmers in Africa. ABS sorghum is intended to have increased levels of essential amino acids, especially lysine (80–100% increase), improved protein digestibility, and increased vitamin A (20 µg of β-carotene per 1 g of dry sorghum), vitamin E, iron (50% increase), and zinc (35% increase) (13). Figure 2 shows food products made from prototype ABS sorghum compared with those from normal sorghum. ABS sorghums are currently undergoing field trials.

Impact of Biofortification on Nutritional Status of Young Children

As part of the ABS project, we investigated the potential impact of biofortification of the cereals described above on the nutritional status of young children, aged 2–5 years, using Burkina Faso as a rural African example. Burkina Faso 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 (25). The latter is a critical indicator of child well-being. Burkina Faso has a population of 15.2 million and an annual cereal production rate of 4.3 million tonnes (6). Sorghum (42%), maize (25%), and pearl millet (27%) make up 94% of cereal production (7) and are the major staples of the rural poor. Improvement of agriculture is a major priority and of significance with regard to biofortified cereals; Burkina Faso currently has legislation in place for the cultivation of genetically modified crops (2).

Surveys were conducted to characterize the children's diets. By far the major food group consumed was cereals, which made up ≈96.5% by weight of the diets of 2–3 year olds and 97.5% of the diets of 4–5 year olds. Thus, all other food groups combined contributed only 3.5% (2–3 year olds) and 2.5% (4–5 year olds) to the diets of young children. Maize was the predominant cereal eaten (79–87% of cereals consumed), followed by much small-

Table I. Potential effects of replacing cereal portion of children's diets with biofortified cereals on intake of certain nutrients by 2–3 and 4–5 year old children in Burkina Faso[a,b]

Group / Nutrient / RDA[c]	Cereal	Total Intake[d]	Intake from Cereal	Sorghum[e]	Maize[e]	Rice[e]	Pearl Millet	Wheat
2–3 year olds[f]				4.56%	87.15%	4.04%	3.94%	0.31%
Lysine (g)	Normal	0.60	0.40	0.02	0.35	0.02	0.02	0.00
64 mg/kg body wt (0.72 g)	BF (ABS, QPM)	0.81	0.61	0.04	NBF	NBF	NBF	NBF
Vitamin A (µg RE)	Normal	4.9	0.7	0.03	0.61	0.03	0.03	0.0
Safe limit 400 µg RE	BF (ABS, GR, PVA)	29.7 (ABS)	25.5 (ABS)	24.8 (6:1)	NBF	NBF	NBF	NBF
		65.5 (GR)	61.3 (GR)	NBF	NBF	60.6 (3.8:1)	NBF	NBF
		359.2 (PVA)	355.0 (PVA)	NBF	354.9 (6:1)	NBF	NBF	NBF
		444.5 (ABS+ GR+PVA)	440.3 (ABS+ GR+PVA)	24.8 (6:1)	354.9 (6:1)	60.6 (3.8:1)	NBF	NBF
Iron (mg)	Normal	2.60	2.27	0.10	1.98	0.09	0.09	0.01
11.6 mg	BF (ABS, IPM)	2.71	2.38	0.15	NBF	NBF	0.15	NBF
Zinc (mg)	Normal	2.80	2.61	0.12	2.27	0.11	0.10	0.01
459 µg/kg body wt (5.14 mg)	BF (ABS)	2.84	2.65	0.16	NBF	NBF	NBF	NBF
4–5 year olds[f]				9.03%	79.28%	7.38%	4.00%	0.31%
Lysine (g)	Normal	0.90	0.69	0.06	0.55	0.05	0.03	0.00
64 mg/kg body wt (0.82 g)	BF (ABS, QPM)	1.24	1.03	0.12	0.83	NBF	NBF	NBF
Vitamin A (µg RE)	Normal	5.70	0.80	0.07	0.64	0.06	0.03	0.00
Safe limit 450 µg RE	BF (ABS, GR, PVA)	77.6 (ABS)	72.7 (ABS)	72.0 (6:1)	NBF	NBF	NBF	NBF
		168.4 (GR)	163.5 (GR)	NBF	NBF	162.8 (3.8:1)	NBF	NBF
		479.7 (PVA)	474.8 (PVA)	NBF	474.7 (6:1)	NBF	NBF	NBF
		714.4 (ABS+ GR+PVA)	709.5 (ABS+ GR+PVA)	72.0 (6:1)	474.7 (6:1)	162.8 (3.8:1)	NBF	NBF
Iron (mg)	Normal	4.70	4.30	0.39	3.41	0.32	0.17	0.01
12.6 mg	BF (ABS, IPM)	5.01	4.61	0.59	NBF	NBF	0.28	NBF
Zinc (mg)	Normal	4.80	4.50	0.41	3.57	0.33	0.18	0.01
380 µg/kg body wt (4.86 mg)	BF (ABS)	4.94	4.64	0.55	NBF	NBF	NBF	NBF

[a] Storage and processing losses were excluded.
[b] RE = retinol equivalent; BF = biofortification; NBF = no biofortification; ABS = ABS sorghum; GR = Golden Rice; IPM = iron fortified pearl millet; PVA = provitamin A maize; and QPM = quality protein maize.
[c] Recommended daily allowance values taken from FAO/WHO (9).
[d] Total nutrients from cereals and other sources.
[e] Conversion factor for provitamin A to vitamin A given in parentheses: 6:1 (9) or 3.8:1 (23).
[f] Values in cereal columns indicate percentage of the total cereals consumed.

er 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, because the survey area is one of the major sorghum-growing areas of Burkina Faso. Focus group discussions revealed that the sorghum grown is sold primarily for the production of the local beer.

More than 70% of the children were energy deficient compared to their recommended daily allowances (RDA). This was primarily due to consumption of maize *tô*, the main food in the diet, which is low in energy (234 kJ/100 g) due to its high moisture content (88%). Fifteen percent of 2–3 year olds and ten percent of 4–5 year olds were protein deficient. Further, the quality of the protein was low because much of it came from maize.

Lack of dietary diversity was also noted by Nana et al. (18) and Sawadogo et al. (21) 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, was the most predominant dish eaten. This was followed by soured 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 (17).

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 a biofortified grain (i.e., maize with QPM or provitamin A maize, sorghum with ABS sorghum, 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 determine 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 was calculated. Food matrices have been shown to affect vitamin A bioavailability. Two conversion factors for β-carotene to retinol were used: 3.8:1, as determined by Tang et al. (23) specifically for Golden Rice, and 6:1, as defined by FAO and WHO for mixed diets (9). Assumptions were made based on published data on the biofortification levels of these nutrients in the specific cereals compared with their "normal" equivalents. This approach did not take into consideration the disease burden of the children, any potential changes in the bioavailability of the nutrients with biofortification, or changes in processing losses resulting from biofortification.

Potential Nutritional Benefits of Biofortification

The findings indicated a strong positive effect on the children's nutritional status in terms of lysine, vitamin A, iron, and zinc intake, assuming that all the children's cereal intake was replaced by current biofortified cereals in the same proportions at which the cereals are currently consumed (Table I). Because maize is the predominant cereal consumed, if it were replaced by QPM maize, the lysine component of the diet would be raised, on average, above the children's RDA. The effect of replacing sorghum with ABS sorghum on lysine intake would be negligible because sorghum is such a 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 because rice is only a very small proportion of the diet. The impact of biofortification of these staple cereals on the other nutrients considered would be negligible because the proportions of sorghum and pearl millet in the diet are so small.

The assumption that all the children's cereal intake would be replaced by biofortified cereals might be overly optimistic. A prediction by HarvestPlus (www.harvestplus.org) indicates the estimated contribution of biofortified cereals to the diet would be 30–40%. This estimate notwithstanding, a meta-analysis of community-based studies of QPM maize consumption conducted in Sub-Saharan Africa, Asia, and Latin America showed 12 and 9% increases in the rate of growth in weight and height, respectively, for infants with mild to moderate under-nutrition when maize was the major staple consumed (12). In addition, according to Akalu et al. (1), who published the first 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 might support a catch-up increase in weight. A comprehensive analysis by Stein et al. (22) of the potential health effects of the introduction of Golden Rice to the diet 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. Additional biofortification of Golden Rice with iron, zinc, high-quality protein, and vitamin E (11), which is currently being studied, potentially could have even greater benefits for the nutritional status of Indian people, as could the consumption of ABS sorghum biofortified with this range of nutrients by peoples for whom the major dietary staple is sorghum.

Conclusions

Sadly, our study, like others, showed that the majority of children living in rural Burkina Faso are severely undernourished as a result of the low amount of food they consume, their lack of dietary diversity, and, consequently, their low intake of many macro- and micronutrients. Replacement of normal cereal staples with biofortified crops would not affect the amount of food consumed per se. However, the strategy of most biofortification programs is to add nutrients to the most profitable and highest yielding varieties available (4), which would address, to some extent, the issue of insufficient food availability. For biofortified cereals to make a broad impact on the nutritional status of undernourished children in rural Africa, ideally the predominant cereals consumed should have enhanced with multiple critical nutrients, as has been done with ABS sorghum and the improved Golden Rice ProVitaMin-Rice.

Acknowledgments and Ethics Declaration

This study was funded by the Bill and Melinda Gates Grand Challenges 9, Africa Biofortified Sorghum (ABS) project through a subgrant from Africa Harvest Biotechnology Foundation International. Ethical approval for this project was obtained from the Ethics Committees of the University of Pretoria and the Institut de Recherche en Sciences de la Santé (IRSS) in Burkina Faso. Written, informed consent was given by each mother/caregiver of each child who took part in the survey. We thank Charlotte Konkobo, Eugenie Bicaba, and Armel Sanou for their practical survey work and Eric Amonsou for his assistance with translation.

References

1. Akalu, G., Taffesse, S., Gunaratna, N. S., and De Groote, H. The effectiveness of quality protein maize in improving the nutritional status of young children in the

Ethiopian highlands. Food Nutr. Bull. 31:418, 2010.
2. Birner, R., Kone, S. A., Linacre, N., and Resnick, D. Biofortified foods and crops in West Africa: Mali and Burkina Faso. AgBioForum 10(3):192, 2007.
3. Black, R. E., Morris, S. S., and Bryce, J. Where and why are 10 million children dying every year? Lancet 361:2226, 2003.
4. Bouis, H. B., Hotz, C., McClafferty, B., Meenakshi, J. V., and Pfeiffer, W. H. Biofortification: A new tool to reduce micronutrient malnutrition. Food Nutr. Bull. 32:S31, 2011.
5. Delisle, H., Zagré, N., Ouedraogo, V., and Tarini, A. Marketing of red palm oil for vitamin A in Burkina Faso: A pilot project involving women's groups. Food Nutr. Bull. 22:388, 2001.
6. FAO. Child nutritional status 2009. Published online at www.fao.org/fileadmin/templates/documents/food-security-statistics. FAO, Rome, Italy, 2009.
7. FAO. FAO stat. Published online at www.faostat.fao.org. FAO, Rome, Italy, 2009.
8. FAO and ILSI. Preventing micronutrient malnutrition: A guide to food based approaches—A manual for food policy makers and programme planners. Published online at www.fao.org.docrep/5244E/X5244e00.htm. International Life Sciences Institute, Washington, DC, 1997.
9. FAO and WHO. Human vitamin and mineral requirements. Published online at www.fao.org. FAO/WHO, Rome, Italy, 2002.
10. Genc, Y., Humphries, J. M., Lyons, G. H., and Graham, R. D. Exploiting genotypic variation in plant nutrient accumulation to alleviate micronutrient deficiency in populations. J. Trace Elem. Med. Biol. 18:319, 2005.
11. Golden Rice Organization. Published online at www.goldenrice.org/Content2-How/how6_mn.html. Golden Rice Organization, 2011.
12. Gunaratna, N. S., De Groote, H., Nestel, P., Pixley, K. V., and McCabe, G. P. A meta-analysis of community-based studies on quality protein maize. Food Policy 35:201, 2010.
13. Henley, E. C., Taylor, J. R. N., and Obukosia, S. The importance of dietary protein in human health. Adv. Food Nutr. Res. 60:21, 2010.
14. IRRI. From the field: Confined field test leads to PhilRice's first Golden Rice harvest. Published online at http://irri.org/news-events/hot topics/golden-rice. International Rice Research Institute, Los Baños, Philippines, 2012.
15. Meda, N., Chevalier, P., and Mathieu-Daude, C. Manifestation oculaires liées à la carence en vitamine A en zone rurale du Burkina Faso. Trop. Med. 60:57, 2000.
16. Mertz, E. T., Bates, L. S., and Nelson, O. E. Mutant gene that changes protein composition and increases lysine content of maize endosperm. Science 145:279, 1964.
17. Murdock, L. L., Seck, D., Ntoukam, G., Ntoukam, G., Kitch, L., and Shade, R. E. Preservation of cowpea grain in sub-Saharan Africa-bean/cowpea CRSP contributions. Field Crops Res. 82:169, 2003.
18. Nana, C. P., Brouwer, I. D., Zagré, N. M., Kok, F. J., and Traoré, A. S. Community assessment of availability, consumption, and cultural acceptability of food sources of (pro)vitamin A: Toward the development of a dietary intervention among preschool children in rural Burkina Faso. Food Nutr. Bull. 26:356, 2005.
19. Nestel, P., Boius, J. V., Meenakshi, J. V., and Pfeiffer, W. Biofortification of staple food crops. J. Nutr. 136:1064, 2006.
20. Ruel, M. L., and Levine, C. E. Assessing the potential of food based strategies to reduce vitamin A and iron deficiencies: A review of current evidence. FCND Discussion Paper 92. International Food Policy Research Institute, Washington, DC, 2000.
21. Sawadogo, P. S., Martin-Prével, Y., Savy, M., Kameli, Y., Traissac, P., Traoré, A. S., and Delpeuch, F. An infant feeding index is associated with nutritional status of 6- to 23-month-old children in Burkina Faso. J. Nutr. 136:656, 2006.
22. Stein, A. J., Sachdev, H. P. S., and Qaim, M. Genetic engineering for the poor: Golden Rice and public health in India. World Dev. 36:144, 2007.
23. Tang, G., Qin, J., Dolnikowski, G. G., Russell, R. M., and Grusak, M. A. Golden Rice is an effective source of vitamin A1-4. Am. J. Clin. Nutr. 89:1776, 2009.
24. Tucker, G. Nutritional enhancement of plants. Curr. Opin. Biotechnol. 14:221, 2003.
25. UNICEF. Burkina Faso: Statistics. Published online at www.unicef.org/infobycountry/burkinafaso_statistics.html. United Nations Children's Fund, New York, 2010.
26. Vasal, S. K. The quality protein maize story. Food Nutr. Bull. 21:445, 2000.
27. Weaver, C. A., Hamaker, B. R., and Axtell, J. D. Discovery of grain sorghum germ plasm with high uncooked and cooked in vitro protein digestibilities. Cereal Chem. 75:665, 1998.
28. Welch, R. M., and Graham, R. D. Agriculture: The real nexus for enhancing bioavailable micronutrients in food crops. J. Trace Elem. Med. Biol. 18:299, 2005.

Janet Taylor is a research officer in the Institute for Food, Nutrition and Well-being at the University of Pretoria in South Africa. Her areas of research interest include biopolymers and nutrition.

John Taylor is theme leader for functional biomolecules and health-promoting foods in the newly formed Institute for Food, Nutrition and Well-being at the University of Pretoria in South Africa. John is an AACC International member can be reached at john.taylor@up.ac.za.

Félix Kini is a senior researcher, responsible for the Chemistry Laboratory at the Institut de Recherche en Sciences de la Santé (IRSS) in Burkina Faso.