Economics of Biofortification

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Abstract: Micronutrient malnutrition affects billions of people world-wide, causing serious health problems. Different micronutrient interventions are currently being used, but their overall coverage is relatively limited. Biofortification – that is, breeding staple food crops for higher micronutrient contents – has been proposed as a new agriculture-based approach. Yet, as biofortified crops are still under development, relatively little is known about their economic impacts and wider ramifications. In this article, the main factors that will influence their future success are discussed, and a methodology for economic impact assessment is presented, combining agricultural, nutrition, and health aspects. Ex ante studies from India and other developing countries suggest that biofortified crops can reduce the problem of micronutrient malnutrition in a cost-effective way, when they are targeted to specific situations. Projected social returns on research investments are high and competitive with productivity-enhancing agricultural technologies. These promising results notwithstanding, biofortification should be seen as a complement rather than a substitute for existing micronutrient interventions, since the magnitude and complexity of the problem necessitate a multiplicity of approaches. Further research is needed to corroborate these findings and to address certain issues still unresolved at this stage.

JEL classifications: I1, I3, O1, O3, Q1.

Keywords: micronutrient malnutrition, public health, biofortification, agricultural technology, impact analysis, developing countries.

1 Introduction

Micronutrient malnutrition is a widespread problem in many developing countries. An estimated four billion people are iron deficient, 2.7 billion are at risk of zinc deficiency, and hundreds of millions lack one or more essential vitamins (WHO, 2002; Hotz and Brown, 2004; UN-SCN, 2004). The prevalence is especially high among the poor, whose diets are usually predominated by relatively cheap staple foods, with insufficient quantities of higher-value nutritious foods. Micronutrient deficiencies are often the cause for increased mortality and morbidity, so that the resulting health burden can be immense. This health burden also entails significant economic costs in the developing world (Horton and Ross, 2003; FAO, 2004). Accordingly, controlling micronutrient malnutrition has been ranked as a top development priority by eminent international economists (Lomborg, 2004). Economic growth and poverty reduction will help reduce the problem in the long run. Yet there are also more targeted micronutrient interventions being implemented, including food supplementation, industrial fortification, and nutrition education programs (Allen, 2003; World Bank, 1994). Recently, an agriculture-based approach has been proposed as a supplementary strategy, namely breeding staple food crops for higher micronutrient contents. This breeding approach has been termed 'biofortification' (Nestel et al., 2006). The potential positive effects of biofortification are obvious: if micronutrient-dense staple crops are widely grown and consumed by the poor, their nutritional status would improve, which could lead to significant health advantages and economic benefits. However, although plant breeders are working on the development of biofortified crop varieties, hardly any of these varieties has yet been released, so that the actual impacts are still uncertain.

In this article, we analyze the implications of biofortification from an economic perspective. In the next section, we provide some more background about the problem of micronutrient malnutrition, before describing the biofortification approach in greater detail and discussing important factors that will influence its future success. A methodological framework for assessing the impacts of biofortification is set out in section 4. This methodology has been used for different empirical studies, results of which are presented in section 5. The last section concludes and discusses research and policy implications.

2 Micronutrient malnutrition

For a long time, the food security debate had primarily focused on undernutrition in terms of calories. Calorie undernutrition is usually the result of an insufficient intake of macronutrients (carbohydrates, protein, and fat) and is associated with a feeling of hunger. Hunger is still a serious problem in large parts of the developing world. According to the FAO, 852 million people worldwide were undersupplied with calories in 2002 (FAO, 2004). Micronutrient malnutrition is often less obvious for the people affected, which is also why the term 'hidden hunger' is sometimes used. For certain micronutrients, deficiencies are even more widespread than calorie undernutrition (Figure 1). The major reason for the high prevalence of insufficient micronutrient intakes is the lack of dietary diversity among the poor. Typical diets in low-income households are dominated by staple foods, which are a cheap source of calories but only provide little amounts of vitamins and minerals. In addition to income constraints, lack of awareness and cultural factors also often limit the consumption of more nutritious foods, even where these are available and accessible. Women and children are the most vulnerable groups: pregnancies, breast-feeding, and menstruation as well as rapid body growth in children increase micronutrient requirements and make it even more difficult to achieve adequate intakes (WHO, 2002).

Here should appear Figure 1.

Even though deficient people are often not aware of their inadequate nutritional status, micronutrient malnutrition can have severe health consequences, including increased susceptibility to infectious diseases, physical and mental impairments, and increased mortality rates (Micronutrient Initiative, 2004). Apart from seriously affecting the well-being of the people directly concerned, micronutrient malnutrition negatively impacts on aggregate productivity and economic development (World Bank, 1994; Horton and Ross, 2003). Hence, efforts to control the problem are justified on humanitarian as well as efficiency grounds.

Several interventions are available to control micronutrient malnutrition. Common interventions include food supplementation, such as distributing vitamin capsules at regular intervals, and industrial fortification, that is, adding micronutrients to foodstuffs during processing. While existing micronutrient interventions have their particular strengths, they also have their weaknesses (Allen, 2003). For instance, large-scale distribution programs are resource-intensive, as they require continuous funding, infrastructure, trained personnel, reliable supplies, and monitoring. Moreover, information, education, and communication programs are necessary to ensure participation by the target groups. For industrial fortification, the main problem is reaching those in need, because the poor and malnourished often consume home-produced foods and only little amounts of processed products. Furthermore, fortified foods are often somewhat more expensive than their non-fortified counterparts, unless fortification is mandatory, which then, however, requires monitoring efforts to ensure compliance by food processors. While dietary diversification is considered the most sustainable approach to control micronutrient malnutrition, necessary behavior changes and income constraints are limiting factors in the short and medium run. In this context, the novel approach of biofortification may be a useful intervention to complement the existing set of strategies.

3 The biofortification approach

3.1 Ongoing research programs

For a long time, no particular role was seen for agricultural technology in the fight against micronutrient malnutrition; grain micronutrient content was simply not an important selection criterion for plant breeders. This has changed more recently, when nutritional quality started to receive higher priority and breeders realized that increased micronutrient densities are not only compatible with superior agronomic traits, but may, in some cases, even enhance yields. Plant varieties that are more efficient in the uptake of trace minerals like iron and zinc can be higher yielding in low-quality soils, because these trace minerals are also required for plant vigor and growth (Welch, 2002; Graham et al., 1999).

A number of research and development (R&D) programs with the objective to increase micronutrient densities in staple food crops through breeding have been launched in recent years. The term 'biofortification' has been coined by the HarvestPlus Challenge Program of the Consultative Group on International Agricultural Research (CGIAR). This program concentrates on increasing iron, zinc, and beta-carotene (provitamin A) contents in six staple crop species, namely rice, wheat, maize, cassava, sweetpotato, and beans, and supports exploratory research in an additional ten crops. At this stage, research under HarvestPlus builds primarily on conventional breeding techniques, exploiting the variability of micronutrient contents found in available germplasm.

However, conventional techniques cannot be used when the micronutrient of interest is absent from a particular crop. A case in point is rice, which produces beta-carotene in leaves and in tiny amounts also in rice husks, but not in the endosperm. Hence, in the Golden Rice project, transgenic techniques have been used to introduce the beta-carotene biosynthetic pathway into the endosperm of grain (Ye et al., 2000; Paine et al., 2005). The Golden Rice project involves European research organizations, the International Rice Research Institute (IRRI), and local partners in developing countries. Another crop-specific project (funded as part of the Global Grand Challenges in Health Initiative) is the Africa Biofortified Sorghum (ABS) Project, which seeks to develop a more nutritious and easily digestible sorghum that contains increased levels of beta-carotene, vitamin E, iron, zinc, and several amino acids.

Furthermore, research has been conducted to genetically engineer iron-rich rice (Goto et al., 1999; Lucca et al., 2001; Murray-Kolb et al., 2002), rice that is rich both in iron and zinc (Vasconcelos et al., 2003), iron-rich maize (Drakakaki et al., 2005), and beta-carotene-rich potato (Ducreux et al., 2005). While this is not a complete list of all related research initiatives, the portfolio is indicative of the attention that biofortification is likely to receive in the future food and nutrition security debate.

3.2 Potential advantages

The major expected and intended impact of biofortification is to increase micronutrient intakes among the poor, thus improving their nutrition and health status. By focusing breeding efforts on staple crops, which are consumed by the poor in larger quantities, the approach is self-targeting. Tying micronutrients to staple crops also reduces people's nutritional vulnerability, because, when economic shocks occur, the poor tend to reduce their consumption of higher-value food commodities that are naturally rich in micronutrients. Furthermore, biofortification could be more sustainable than alternative micronutrient interventions. With a one-time R&D investment, biofortified germplasm can be shared internationally, and the varieties could spread through existing seed distribution systems. Since biofortified seeds can easily be reproduced, poor farmers in remote rural areas, with limited access to formal seed markets, could also be reached. Thus, unlike other micronutrient interventions, which require large funds on an annual basis, biofortification could produce a continuous stream of benefits with minimal recurrent costs.

Biofortification promises to be a pro-poor and pro-rural approach, which could complement existing interventions. However, biofortified crops are still at the stage of R&D, so that these potential advantages have not yet materialized. The only exception are beta-carotene-rich, orange-fleshed sweetpotatoes, which have been promoted in different countries (e.g., Low et al., 1997).

3.3 Factors influencing future impacts

Whether biofortified crops will really contribute to an improved nutrition and health situation in developing countries will primarily depend on their efficacy and coverage in particular situations (Figure 2). Efficacy will be determined by the amount of the micronutrient in the crop, micronutrient retention after processing, and its bioavailability. Coverage, in turn, is mainly a function of farmer adoption and consumer acceptance of biofortified varieties.

Here should appear Figure 2.

Micronutrient content. Many varieties of staple food crops already contain certain amounts of micronutrients. For instance, high-yielding wheat varieties contain about 38 parts per million (ppm) of iron and 31 ppm of zinc. Popular rice varieties contain 3 ppm of iron and 13 ppm of zinc in the milled grain. The potential to further increase these micronutrient contents by conventional breeding exists. Adequate genetic variations in concentrations of beta-carotene, other carotenoids, iron, zinc, and other minerals has been identified among cultivars, making selection of nutritionally appropriate breeding materials possible. For example, available orange-fleshed sweetpotato varieties contain over 100 μg/g of beta-carotene. Nevertheless, with conventional breeding, achievable micronutrient contents are limited by the available genetic variation within each crop species. Transgenic techniques can help to further increase these levels, or to introduce micronutrients not naturally occurring in the crop. A case in point is Golden Rice: biotechnologists managed to produce a transgenic rice line containing up to 31 μg/g of beta-carotene in the endosperm (Paine et al., 2005). Where exactly the micronutrient is located within the grain matters considerably. If it is found mainly in the aleurone layer of the grain, the nutritional impact can be small, since the outer layers are removed during the process of milling and polishing; the impact is greater when it is located in the endosperm. Micronutrient toxicities are not expected at levels achieved through biofortification. For beta-carotene, toxicity is not an issue at all, because the human body only absorbs as much beta-carotene as it needs.

Micronutrient retention. Micronutrient contents in the food actually consumed might be lower than those produced in the crop, because post-harvest and processing losses can occur. Beta-carotene in particular is sensitive to bright sunlight and extreme heat. For orange-fleshed sweetpotatoes, beta-carotene retention after boiling is around 80% (Nestel et al., 2006), but losses can be much higher with inappropriate storage and cooking techniques. Also for minerals, losses can occur, although they are usually less sensitive than vitamins and carotenoids.

Bioavailability. How much of particular micronutrients the human body can absorb and use for body functions depends on a number of factors. The exact chemical composition of the micronutrient matters and also how the compound is stored within the plant cell. Furthermore, enhancing and inhibiting factors in people's diets can have an important influence. Beta-carotene absorption, for instance, depends on minimum fat intakes, while alcohol reduces bioavailability. Iron bioavailability is positively influenced by vitamin C intake, but phytates and tannins act as inhibiting factors. Haas et al. (2005) have shown that high-iron rice can indeed improve the iron status of women. Similarly, van Jaarsveld et al. (2005) have shown that the consumption of orange-fleshed sweetpotato improves the vitamin A status of children: with 100 μg/g of beta-carotene and 80% retention when consumed in boiled form, even a 50 gram consumption of this crop is sufficient for meeting 75% of the recommended daily allowance of vitamin A for children. Also for Golden Rice, a relatively high bioavailability of the beta-carotene produced has been demonstrated in preliminary feeding trials (R. Russell, personal communication). While further research is needed to verify these findings in community settings, preliminary results from the dissemination of orange-fleshed sweetpotato in Mozambique are suggestive of substantial nutritional impacts among micronutrient-deficient target populations.

Farmer adoption. In order for farmers to adopt biofortified crops, micronutrient traits have to be bred into advanced lines, which are agronomically superior. Nutritional improvement at the cost of lower yields or other agronomic disadvantages is a non-starter. For example, wheat breeders are attempting to biofortify varieties resistant to a rust that is expected to affect large areas in Pakistan and India. Thus, adoption of biofortified wheat there is expected to be driven by rust resistance. It is rather unlikely that farmers are willing to pay higher prices for biofortified seeds, unless these seeds directly contribute to higher incomes. Also critical is local adaptation: varieties will have to be targeted to specific agroecological and socioeconomic conditions. The greater the number of locally-adapted biofortified varieties, the higher the likely adoption. For wide coverage, plant breeders will need to focus first on biofortifying 'mega' varieties, such as BR28 and BR29 of rice in Bangladesh, which together occupy almost 60% of the rice area in the Boro season, or BR11, which accounts for over a quarter of the Aman season rice area (IRRI, personal communication). Finally, the speed of adoption will depend on the efficiency of existing seed distribution channels and farmers' seed replacement rates. Although biofortified seeds can be reproduced on-farm, some initial public support might be needed for the new varieties to penetrate formal and informal seed markets.

Consumer acceptance. For reasons outlined earlier, awareness of micronutrient deficiencies is generally low, so that the nutritional advantages of biofortification might not be fully appreciated. But even if they are, the willingness and ability to pay higher prices for biofortified foods are likely to be limited among the poor, who bear the brunt of micronutrient malnutrition. Also at equal prices, consumers will only purchase micronutrient-dense crops, if they meet their personal preferences in terms of taste, texture, and visual appearance. Mineral biofortification at realistic levels is not expected to change consumer characteristics, that is, iron and zinc traits are invisible (Nestel et al., 2006). This is different for beta-carotene, which changes the color of the crop to deep yellow or orange, so that it will be necessary to invest more in demand creation for these varieties through communication and marketing efforts.

Consumer acceptance also influences farmer adoption decisions, as low acceptance would translate into lower market prices.

4 Methodology for impact assessment

In agricultural economics, the usual approach to assess the impact of new crop technologies is to quantify the economic benefits arising from productivity increases as a result of technology adoption by farmers. Such productivity increases – either through yield gains or savings in production costs – cause a downward shift in the crop supply curve, based on which aggregate economic surplus and surplus distribution effects can be derived (Alston et al., 1995). However, the main focus of biofortification is on improving the nutritional status of consumers through quality enhancement. Quality improvements generally lead to a marginal benefit increase for consumers, which different authors have modeled as an upward shift in the crop's demand function (e.g. Unnevehr, 1986). Yet it is unlikely that biofortification would result in an upward shift in demand, because of awareness and purchasing power constraints among the poor, as discussed above. In this case, benefits of biofortification should rather be considered as positive nutrition and health outcomes for individuals suffering from micronutrient malnutrition and related externalities for society at large. Such externalities are more complex to evaluate.

Dawe et al. (2002) looked at the potential nutritional effects of Golden Rice by analyzing likely improvements in vitamin A intakes in the Philippines. This approach implicitly builds on a measure of program success, which is commonly used also for other micronutrient interventions, namely the achieved reduction in the number of people with micronutrient intakes below a defined threshold (e.g. Fiedler et al., 2000). However, since micronutrient intake is not an end in itself but only a means to ensure healthy body functions, it is more appropriate to go further and quantify health outcomes directly. In a preliminary assessment of iron biofortification in India and Bangladesh, Bouis (2002) estimated the reduction in the number of anemia cases and attributed a monetary value to each case averted for a cost-benefit analysis. Zimmermann and Qaim (2004) suggested a more comprehensive approach in their analysis of the potential health benefits of Golden Rice in the Philippines: since micronutrient malnutrition causes significant health costs, which could be reduced through biofortification, they quantified the health cost of vitamin A deficiency with and without Golden Rice and interpreted the difference – that is, the health cost saved – as the technological benefit.

4.1 Quantification of health costs

There are different methodologies available for the quantification of health costs, including budgeting medical treatment costs, estimating productivity losses, and willingness to pay approaches (e.g., Brent, 2003). A framework which appears appropriate to quantify the health costs of micronutrient malnutrition in developing countries is the disability-adjusted life years (DALYs) approach. DALYs are used to establish the burden of a disease by measuring the health loss through mortality and morbidity in a single index (Murray and Lopez, 1996). The annual health costs of a disease are expressed in terms of the number of DALYs lost:

$$(1) \qquad \textit{Health costs} = \textit{DALYs}_{lost} = \textit{YLL} + \textit{YLD}_{weighted}$$

where *YLL* are years of life lost due to premature deaths and *YLD* are years lived with disabilities resulting from the disease, which are weighted according to the severity of disabling conditions.

The DALYs approach has been used in very different contexts, such as quantifying the health costs of malaria or HIV/AIDS (e.g., Lomborg, 2004). The World Health Organization has used it to assess the global health costs of different risk factors, including undernutrition and micronutrient malnutrition (WHO, 2002). In their Golden Rice study, Zimmermann and

Qaim (2004) have refined the DALYs methodology to consider more explicitly different adverse health outcomes of vitamin A deficiency. Stein et al. (2005) have further developed the approach by incorporating new nutrition insights and extending it also to iron and zinc malnutrition. For each micronutrient, the number of DALYs lost can be calculated as:

(2) $$DALYs_{lost} = \underbrace{\sum_j T_j M_j \left(\frac{1-e^{-rL_j}}{r} \right)}_{YLL} + \underbrace{\sum_i \sum_j T_j I_{ij} D_{ij} \left(\frac{1-e^{-rd_{ij}}}{r} \right)}_{YLD}$$

where T_j is the total number of people in target group j, and M_j is the mortality rate associated with the particular deficiency. I_{ij} is the incidence rate of adverse health outcome i in target group j, D_{ij} is the corresponding disability weight, and d_{ij} is the duration of the outcome. For permanent health problems, d_{ij} equals the average remaining life expectancy L_j. Future life years lost are discounted at a discount rate of r. An overview of adverse health outcomes of iron, zinc, and vitamin A deficiency is shown in Table 1. Only those outcomes for which a definite causal relationship has been established in meta-analyses are included (Stein et al., 2005a).

Here should appear Table 1.

Inserting appropriate health and demographic statistics in equation (2), the health costs of micronutrient malnutrition in a country or region can be calculated. Since biofortified crops are not yet consumed, this status quo situation is the benchmark without biofortification. Improved micronutrient intakes through consumption of biofortified crops will reduce mortality and incidence rates of adverse functional outcomes, so that the number of DALYs lost decreases.[1] The difference in micronutrient-related health costs – that is, the number of DALYs saved – is considered as the benefit of biofortification.

[1] How the reduction in mortality and incidence rates can be derived is explained in the next sub-section.

4.2 Improved nutrition and health status through biofortification

Micronutrient intakes required for healthy body functions vary from individual to individual, based on age, sex, physical activity, and many other factors. Recommended dietary reference intake levels for each micronutrient are usually specified for particular target groups. If the actual intake of an individual is below the recommended one, the person is likely to be deficient. An illustrative distribution of micronutrient intakes is shown in panel (a) of Figure 3. In this example, a certain fraction of the population is deficient at current intake levels without biofortification.

Here should appear Figure 3.

Future consumption of biofortified crops will shift the intake distribution to the right, whereby the magnitude of the shift will depend on the actual improvement in bioavailable micronutrients, which is a function of efficacy and coverage, as discussed above. Some individuals, who were deficient previously, will achieve sufficiency status; for them, possible adverse health outcomes will cease. However, especially individuals at the lower end of the intake distribution might still remain deficient, even after the shift. Also for these individuals there will be an improvement in health status, though, because the prevalence and severity of adverse health outcomes is correlated with the degree of micronutrient deficiency. In fact, a convex relationship between micronutrient intake and adverse health outcomes can be assumed (Hallberg et al., 2000; Zimmermann and Qaim, 2004), as shown in panel (b) of Figure 3. The effectiveness of biofortification in improving health status can then be calculated as the ratio of the areas *A* and (*A* + *B*). The mean effectiveness for a particular target group (E_j) can be used to derive new, reduced incidence rates of adverse health outcomes as $I_{ij}^{new} = (1 - E_j) \cdot I_{ij}$. For the reduction in mortality rates, the same formula can be used.[2]

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[2] While the approach described here can be used for all micronutrients, Stein et al. (2005a) proposed an

4.3 Cost-effectiveness and returns on R&D investments

A comprehensive economic analysis of projects or policies requires that aggregate benefits are juxtaposed with aggregate costs. The major cost of biofortification is the investment in breeding and disseminating micronutrient-dense varieties. If the discounted biofortification investments are divided by the discounted number of DALYs saved, the average cost per DALY saved can be calculated, which is a common measure for the cost-effectiveness of health programs (e.g., World Bank, 1993). Based on this per-DALY cost, it is possible to compare the cost-effectiveness of biofortification with that of alternative micronutrient interventions, other public health measures, or pre-defined thresholds for what is considered cost-effective.

One of the advantages of the DALYs approach is actually that health and life do not have to be expressed in monetary terms, since this is always associated with ethical concerns. Yet, since biofortification is an agricultural technology, which also competes with non-health related, productivity-enhancing technologies in terms of funding, a comparison of the returns on R&D investments might be desirable in some cases. This requires that a monetary value be attributed to each DALY saved, in order to convert the health benefits into a dollar figure. What value to choose per DALY saved is not a straightforward decision. In developing country contexts, a standardized rate of $1000 has sometimes been used (e.g., World Bank, 1994). Other authors have valued DALYs at the average per-capita income in a country (e.g., Zimmermann and Qaim, 2004). These are certainly lower-bound values, and they should not be considered as an approach to quantify the intrinsic value of life. But, since higher values translate into larger monetary benefits, the results are more cautious and convincing if favorable returns can already be shown at these lower-bound values.

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alternative method for iron, which derives the reduction in the prevalence of adverse health outcomes through biofortification by using the cumulative distribution function of iron intakes in a population. Where data availability permits, this alternative method is preferable for iron, but it is not suitable for zinc and vitamin A.

5 Empirical analyses

5.1 Biofortification in India

Using the methodology outlined in the previous section, first comprehensive studies on the impacts of biofortification have been carried for in India (Stein et al., 2005b; 2006a; 2006b), where micronutrient malnutrition is a widespread problem. About half of all women in India and three quarters of all children are anemic (IIPS, 2000),[3] the risk of zinc deficiency is high (Hotz and Brown, 2004), and almost one-third of all preschool children are vitamin A deficient (UN-SCN, 2004). In the framework of the HarvestPlus Challenge Program, crop scientists at IRRI and CIMMYT are using conventional tools to breed higher amounts of iron and zinc into rice and wheat. The resulting breeding lines will be shared with the Indian public research system for backcrossing the micronutrient traits into local varieties. In addition, transgenic Golden Rice breeding lines, with high amounts of beta-carotene, will be transferred to India through the Golden Rice Humanitarian Board. Adaptive research, testing, and deregulating the technologies will still take some time; it is expected that the first biofortified varieties might be released in India in 2010. Both rice and wheat are important staple foods in India, so that significant positive nutrition and health benefits can be expected in the future.

Since much of the information needed for impact assessment is not observable at this stage, assumptions have to be made for ex ante analyses. Based on expert interviews, two impact scenarios were constructed – one with optimistic and the other one with more pessimistic assumptions. The major assumptions made on technology efficacy and coverage are shown in Table 2. Furthermore, estimated financial costs are shown. These costs include only part of the international R&D investments, because the biofortified breeding lines will be

[3] Iron deficiency anemia is only a subgroup of anemia. But, because it is the most important form, anemia is often used as proxy for iron deficiency. It should be noted, however, that individuals can also suffer from iron deficiency without being anemic (Nestel and Davidsson, 2002).

shared also with other developing countries. In addition, national program costs for adaptive breeding, testing, and dissemination have been considered. For Golden Rice, the aggregate costs are higher than for iron and zinc biofortification for two reasons. First, since Golden Rice is a transgenic technology, more costly biosafety and food safety tests have to be carried out under the national regulatory requirements. Second, since the beta-carotene turns the color of the rice grain yellow, public marketing efforts will be necessary to promote farmer and consumer acceptance. More intensive marketing efforts are expected to increase technology coverage. Since the projected marketing expenditures account for a large part of the total cost, the cost estimates for Golden Rice are higher in the optimistic than in the pessimistic scenario.

Here should appear Table 2.

Based on recent health and demographic statistics, the current health costs of micronutrient malnutrition in India were calculated. This was done separately for the three micronutrients iron, zinc, and vitamin A. The results are shown in Table 3. With an annual loss of 4 million DALYs, the aggregate costs of iron deficiency are higher than those of zinc and vitamin A deficiency. Although the latter two are associated with higher mortality, especially among children, they are less widespread than iron deficiency. For an ad-hoc estimate of the total health costs of all three micronutrient deficiencies together, the individual results can be added up, resulting in an annual loss of over 9 million DALYs. This indicates that hidden hunger is indeed a huge public health problem in India. The DALYs sum will underestimate the true costs, however, because – owing to micronutrient interactions – multiple deficiencies in individuals can lead to additional adverse health outcomes, which are not captured here. Only recently have nutritionists started to pay more attention to micronutrient interactions. At this stage, the knowledge available is not sufficient to incorporate these interactions into economic analyses. This is also the reason why iron, zinc, and provitamin A biofortification have been analyzed separately, although all three micronutrients might eventually be bred into the same crop varieties.

Here should appear Table 3.

For the impact analyses, a nationally representative data set was used, which includes detailed food consumption data for 120,000 Indian households (NSSO, 2001). Using local food composition tables and consumer equivalence units, the consumption of different food commodities was translated into micronutrient intakes for individuals. The results on health cost reductions through biofortification for the two impact scenarios are shown in the lower part of Table 3. Under optimistic assumptions, biofortified rice and wheat varieties could more than halve the health costs associated with micronutrient malnutrition in India. Even under pessimistic assumptions, the reduction is still significant, ranging between 9-19%. These findings suggest that biofortification is an effective way to reduce hidden hunger, albeit it is unlikely to eliminate the problem completely. The differences in impacts between the two scenarios are mainly due to the underlying assumptions on micronutrient contents in the grain and coverage rates of biofortified varieties. Since these parameters can still be influenced through appropriate policies, the results also demonstrate that public support is important for increasing the positive impacts.

Results of cost-effectiveness analyses for the individual technologies are also shown in Table 3. The cost per DALY saved through biofortification is very low. The World Bank (1993) classifies health interventions as cost-effective, when the cost of saving one DALY is lower than US$ 200.[4] Thus, biofortification is highly cost-effective, even under pessimistic assumptions. Also, the cost-effectiveness of biofortification compares favorably with other micronutrient interventions. For instance, the cost per DALY saved through iron supplementation and industrial fortification efforts ranges between US$ 5.6-16.3 (Gillespie, 1998). For zinc supplementation and fortification programs, it ranges between US$ 5.0-18.0, and for vitamin A interventions between US$ 84-599 (Tan-Torres Edejer et al., 2005). The

[4] The World Bank (1993) gives a threshold of US$ 150 (in 1990 dollars); in current terms this corresponds to more than US$ 200.

major reasons for the high cost-effectiveness of biofortification are the enormous health gains it generates and the low recurrent cost that accrues once micronutrient-dense varieties have been developed and fed into existing seed distribution systems.[5] This was discussed in greater detail in section 3.

Additionally, internal rates of return (IRRs) for R&D investments in biofortification have been calculated using the lower-bound monetary values mentioned above for valuing each DALY saved, namely the international standard of US$ 1000 and the average Indian per-capita income of US$ 620. Under optimistic assumptions in particular, IRRs are very high (Table 3). Even under pessimistic assumptions, they are still comparable to the average returns on R&D investments in productivity-enhancing agricultural technologies (Alston et al., 2000). These are clear indications that biofortification can be a worthwhile investment from a social point of view.

5.2 Overview of other studies

Further ex ante studies on the impacts of biofortification have been carried out at different CGIAR centers for HarvestPlus target crops and countries. These studies were mainly conducted for research priority setting within the HarvestPlus Challenge Program. The methodological approach in these additional studies was largely the same as the one outlined here, although data constraints necessitated the use of average food consumption data instead of individual household observations. Therefore, projections of nutritional improvements are based on mean values for the individual target groups rather than the entire sample distribution of micronutrient intakes. Additional details on assumptions are provided in Meenakshi et al. (2006). Results in terms of health benefits and cost-effectiveness are shown in Table 4 for selected crops and countries. All the examples shown are based on

[5] Of course, where seed distribution systems are dysfunctional, coverage rates of biofortification will be lower or dissemination costs will be higher, both of which would result in a less favorable cost-effectiveness.

micronutrient amounts that breeders reckon they can achieve using conventional breeding techniques.

Here should appear Table 4.

These additional results confirm that biofortification can reduce the problem of micronutrient malnutrition in developing countries. Most of the examples also suggest that biofortification is a cost-effective approach, certainly in Asia and Africa, and also in certain contexts in Latin America. However, there are also striking differences between the individual results. Comparison of the studies for rice in Bangladesh and the Philippines, for instance, demonstrates the influence of local dietary patterns. While rice is the main food staple for the poor in Bangladesh, average rice quantities consumed in the Philippines are lower, because maize is also an important staple in certain parts of the country. Similarly, cassava is only one staple crop among other important ones for poor households in the Northeast of Brazil. More detailed assessments on appropriate approaches have to be case-specific. It is clear, however, that there is no single crop or technique that will work in every situation. Indeed, in certain situations, biofortification may not enjoy a cost advantage over other interventions.

6 Conclusions and research challenges ahead

Micronutrient malnutrition is a widespread problem in developing countries, especially among women and children in the poorer segments of the population. The social costs associated with adverse health outcomes are often sizeable. Biofortification is a new, agriculture-based intervention, which is likely to gain in importance in the future, as indicated by the large number of related international research programs recently launched. As biofortified crops are still under development, relatively little is known about their economic impacts and wider ramifications. In this article, we have discussed the main factors that will influence their future success and have illustrated a suitable methodology for economic impact assessment, which combines agricultural, nutrition, and health aspects. Ex ante studies from India and other developing countries suggest that biofortified crops can reduce the problem of micronutrient malnutrition in a cost-effective way, when they are targeted to specific situations.

The approach presented here is only a first step to explicitly consider nutrition and health aspects in impact assessments of agricultural technology. More basic research could help to further improve and extend the methodology and develop welfare measures which include health and quality of life components. Moreover, additional empirical work is required to verify the preliminary results reported here, including ex post studies building on observable data once biofortified crops are disseminated. In the case of the deployment of orange-fleshed sweetpotato, HarvestPlus researchers are planning a randomized evaluation of impact, an approach not commonly used in agricultural economics. Such ex post analysis will pose new challenges, especially with respect to indicators of success, as impact on crop adoption, food and micronutrient intakes, and nutritional outcomes have rarely been assessed under a unifying paradigm. This interdisciplinary research – involving economists, other social scientists, agronomists, and nutritionists – is critical for a more comprehensive analysis of the multiplicity of impacts of biofortification.

Apart from impact analyses, there are also other open issues, which require further research. These include questions of bioavailability and micronutrient interactions in the human body. For instance, enhanced iron and zinc content go hand-in-hand for several crops, and their combined impact may be greater than what a single nutrient alone may achieve. Similarly, nutrient interactions are important in understanding the impact of biofortifying multiple crops. In many countries, diets often feature a primary and one or more secondary staple crops – cassava is commonly eaten with beans in many parts of Africa and Latin America, for example. The higher beta-carotene content of cassava may enhance the absorption of the iron in beans. Likewise, nutrient interactions in plants and linkages between high micronutrient concentrations and other crop characteristics are not yet fully understood. And finally, it is still unclear how stable the micronutrient traits will be when seeds are repeatedly reproduced by farmers. A rapid trait dilution would certainly put the assumed sustainability of the biofortification approach into question.

Where there are technical constraints in breeding, transgenic approaches could help to increase the amounts beyond what is possible through conventional breeding alone. Transgenic approaches are also needed when a particular micronutrient does not occur naturally in a crop. Cases in point are the lack of beta-carotene in the endosperm of rice and wheat. While transgenic approaches may further increase the impact of biofortification, they may also involve additional complications in terms of regulatory requirements and consumer acceptance.

In spite of further research challenges ahead, an important policy implication, which already emerges from the evidence so far, is that biofortification can play an important role in achieving nutrition security in particular situations. Apart from the high expected cost-effectiveness, preliminary cost-benefit analyses show that social returns on R&D investments into biofortification are favorable and highly competitive with productivity-enhancing agricultural technologies. Therefore, further pursuing the strategy of biofortification appears to be worthwhile. Related funding will have to come primarily from the public sector or humanitarian organizations. Although the projected social benefits are sizeable, neither farmers nor poor consumers are likely to have a higher willingness to pay for biofortified crops, so that incentives for the private sector to invest are rather limited.

To conclude, biofortification should not be seen as substitute for existing micronutrient interventions but as a complementary strategy. No single approach will eliminate the problem of micronutrient malnutrition, as our results also indicate. All interventions have their strengths and weaknesses in particular situations. While supplementation and industrial fortification might be more suitable for urban areas and feeding programs for well defined target groups, biofortification is likely to achieve a wider coverage, including in remote rural areas, which are often underserved by other interventions. It is only in the long run that poverty reduction and economic growth may be expected to contribute to dietary diversification; in the interim, other interventions need to be implemented.

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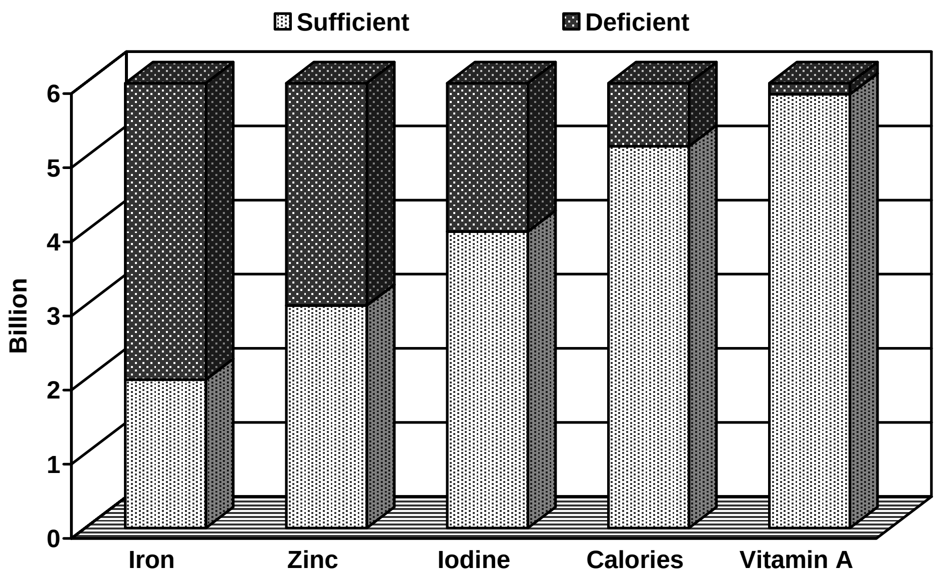
Tables and figures

Figure 1. Number of people suffering from different forms of malnutrition worldwide



Sources: WHO (2002), Hotz and Brown (2004), UN-SCN (2004), FAO (2004).

Figure 2. Factors influencing the impact of biofortified crops

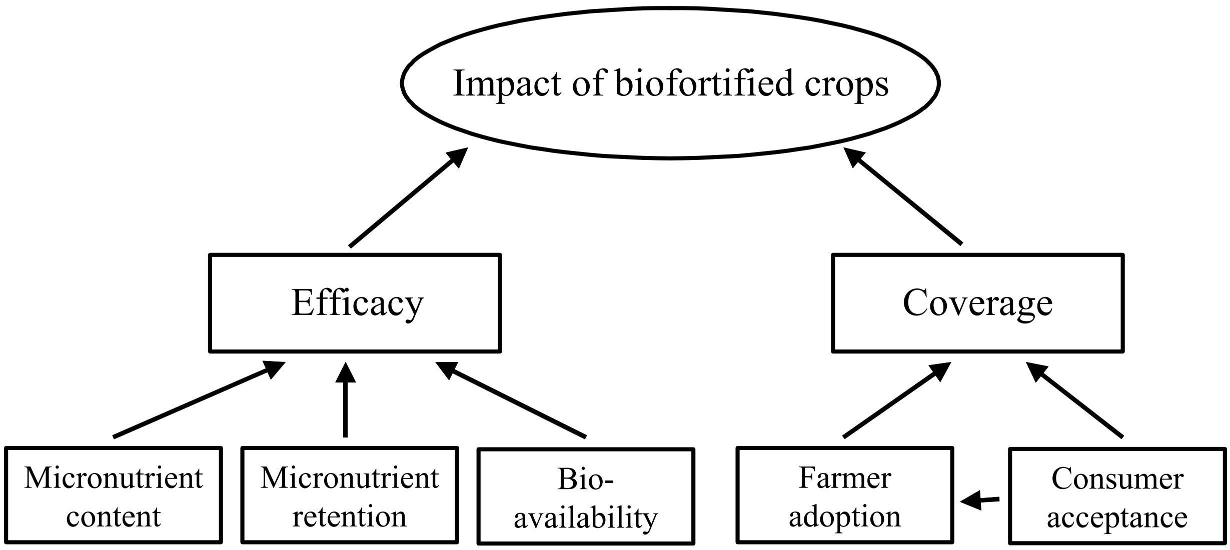
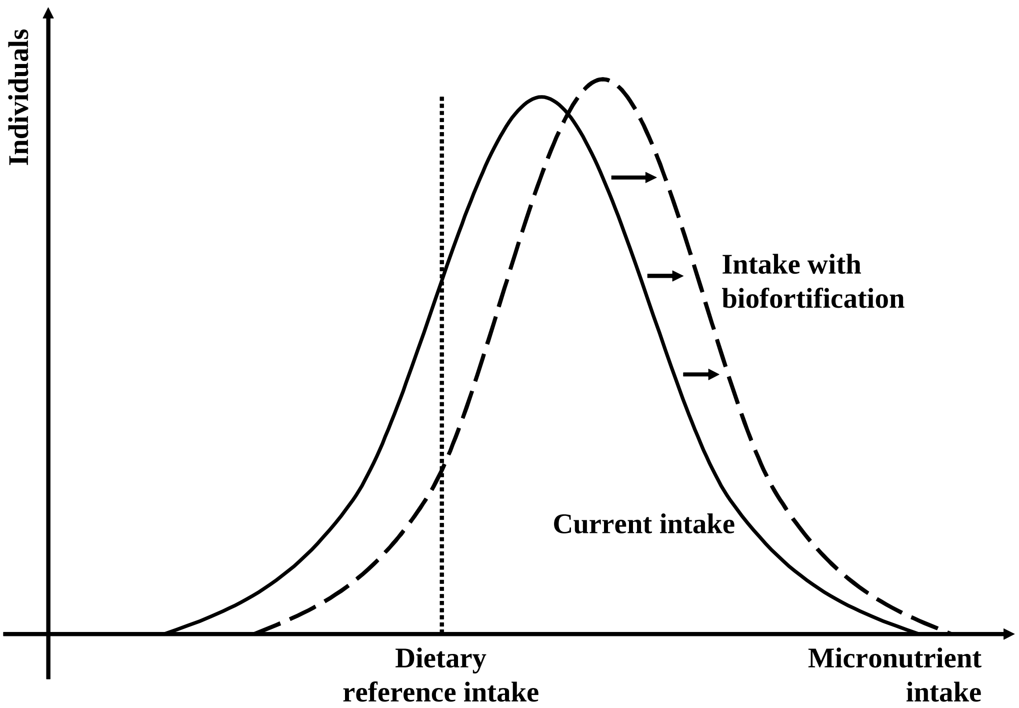


Figure 3. Improvement in micronutrient intakes and health outcomes through biofortification

(a) Shift in the distribution of micronutrient intakes



(b) Relationship between micronutrient intake and health outcome

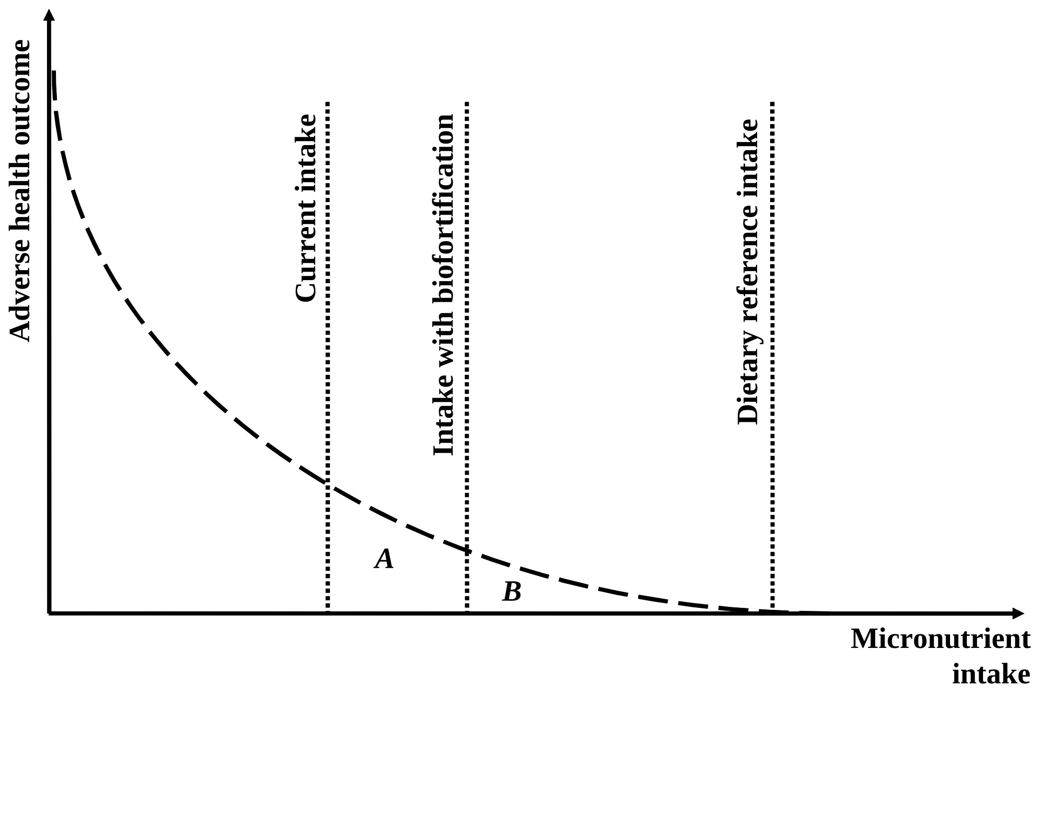


Table 1. Adverse health outcomes of micronutrient deficiencies for different target groups

Target group	Iron deficiency	Zinc deficiency	Vitamin A deficiency
Children	• Impaired physical activity • Impaired mental development • Child mortality (related to maternal deaths)	• Diarrhea • Pneumonia • Stunting • Child mortality	• Child mortality • Measles • Night blindness • Corneal scarring • Blindness
Women	• Impaired physical activity • Maternal mortality		• Night blindness in pregnant and lactating women
Men	• Impaired physical activity		

Source: Stein et al. (2005a).

Table 2. Assumptions used to simulate the impact of biofortification in India

	Iron-rich rice	Iron-rich wheat	Zinc-rich rice	Zinc-rich wheat	Golden Rice
Baseline MN content	3 ppm Fe [a]	38 ppm Fe [b]	13 ppm Zn [a]	31 ppm Zn [b]	0 µg/g βC [a]
			Optimistic scenario		
Improved MN content	8 ppm Fe [a]	61 ppm Fe [b]	35 ppm Zn [a]	68 ppm Zn [b]	31 µg/g βC [a]
MN retention	100%	100%	100%	100%	65%
Coverage	50%	50%	50%	50%	50%
R&D cost (net present value)	US$ 3.6 m	US$ 4.5 m	US$ 3.6 m	US$ 4.5 m	US$ 27.9 m
			Pessimistic scenario		
Improved MN content	6 ppm Fe [a]	46 ppm Fe [b]	20 ppm Zn [a]	37 ppm Zn [b]	14 µg/g βC [a]
MN retention	100%	100%	100%	100%	20%
Coverage	20%	30%	20%	30%	14%
R&D cost (net present value)	US$ 12.6 m	US$ 13.8 m	US$ 12.6 m	US$ 13.8 m	US$ 21.4 m

Notes: MN = micronutrient, ppm = parts per million, Fe = iron, Zn = zinc, µg = microgram, βC = beta-carotene.
[a] Micronutrient contents shown are for milled rice. [b] Micronutrient contents shown are for whole grain.
Sources: Stein et al. (2005b; 2006a; 2006b).

Table 3. Impact of biofortification in India

	Iron biofortification [a]	**Zinc biofortification** [b]	**Provitamin A biofortification** [c]
Health cost of deficiency without biofortification (DALYs lost)	4.0 m	2.8 m	2.3 m
		Optimistic scenario	
DALYs saved through biofortification	2.3 m	1.6 m	1.4 m
Reduction in health cost (%)	58	55	59
Cost per DALY saved (US$/DALY)	0.46	0.68	3.06
IRR (%, DALY valued at US$ 620)	149	135	70
IRR (%, DALY valued at US$ 1000)	168	153	77
		Pessimistic scenario	
DALYs saved through biofortification	0.8 m	0.5 m	0.2 m
Reduction in health cost (%)	19	16	9
Cost per DALY saved (US$/DALY)	5.39	8.80	19.40
IRR (%, DALY valued at US$ 620)	53	46	31
IRR (%, DALY valued at US$ 1000)	61	53	35

Notes: [a] Iron biofortification of rice and wheat is considered. [b] Zinc biofortification of rice and wheat is considered. [c] Biofortification of rice with beta-carotene is considered (Golden Rice).

Sources: Stein et al. (2005b; 2006a; 2006b).

Table 4. Impact of biofortification in selected crops and countries

	Reduction in health cost (%)		Cost per DALY saved (US$)	
	Optimistic	**Pessimistic**	**Optimistic**	**Pessimistic**
		Iron		
Rice, Bangladesh	21	8	3	10
Rice, Philippines	11	4	49	197
Beans, Northeast Brazil	36	9	13	56
Beans, Honduras	22	4	20	114
		Zinc		
Rice, Bangladesh	46	15	2	6
Rice, Philippines	39	11	7	46
Beans, Northeast Brazil	20	5	95	799
Beans, Honduras	15	3	48	423
		Provitamin A		
Sweetpotato, Uganda	64	38	4	10
Maize, Kenya	32	8	10	44
Cassava, Nigeria	28	3	3	35
Cassava, Northeast Brazil	19	4	84	434

Source: Meenakshi et al. (2006).