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Health benefits of biofortification – an *ex-ante* analysis of iron-rich rice and wheat in India

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50-word-summary: *"Hidden hunger" affects billions world-wide. Next to supplementation and fortification, "biofortification" – breeding higher micronutrient levels into staple crops – could be a cost-effective answer by agricultural means. Using disability-adjusted live years (DALYs) to measure related health benefits, this is shown in an* ex-ante *analysis of iron biofortified cereals in India.*

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***Abstract**: Hunger is acknowledged to impose a heavy burden on humankind with severe negative health consequences. Micronutrient malnutrition, or "hidden hunger", is an even more widespread problem, to which economic development and income growth alone are not expected to provide a solution any time soon. Existing micronutrient interventions like pharmaceutical supplementation or industrial fortification have their limitations and can be complemented by a new approach: breeding food crops for higher micronutrient densities. Knowledge about the cost-effectiveness of this new tool, also termed biofortification, is scarce. In this study, a framework for economic impact analysis is developed, which is then used for evaluation of iron-rich rice and wheat in India. Health benefits are measured and quantified using "disability-adjusted life years" (DALYs). The impact of biofortification is based on a representative data set of food consumption at the household level. Juxtaposing imputed health benefits with research and development costs proves the cost-effectiveness of the intervention; under pessimistic assumptions saving one healthy life year through biofortification only costs US$ 1.90, a cost which even declines to 36 Cents under optimistic assumptions. Extending the study to include a cost-benefit analysis shows that iron biofortification, with an internal rate of return of 74-152%, can also be a worthwhile public investment.*

***Keywords:** biofortification, micronutrients, plant breeding, health benefits, DALYs, iron deficiency, iron-rich rice, iron-rich wheat, cost-effectiveness, cost-benefit analysis, India.*

***JEL codes**: I120, I180, I310, O150, O220, O330, Q180.*

Despite the successes of the Green Revolution and continued efforts to fight poverty, hunger remains widespread, with an estimated 800m undernourished people in the developing world (United Nations SCN). The problem of "hidden hunger" – as micronutrient malnutrition is referred to – is, however, much larger. An estimated 3.5 billion people in developing countries are affected by iron deficiency (ID), 2.2 billion people suffer from iodine deficiency and over 250m children are affected by vitamin A deficiency (WHO 1998, Underwood, United Nations ACC/SCN). The consequences of this hidden hunger – in terms of mortality, impaired physical and cognitive development, or eye problems – assume staggering magnitudes.

While there is a correlation between hidden hunger and poverty, it is well-recognised that relying on economic development and income growth alone is not likely to rid the world of micronutrient malnutrition any time soon (Weinberger 2003, Haddad et al.). There are, however, several alternative interventions to fight micronutrient deficiencies. These include industrial fortification of foods (such as sugar, or wheat flour), pharmaceutical supplementation, the promotion of dietary diversification, and nutrition education. These interventions vary in terms of their potential coverage, monitoring and other costs, and the degree to which compliance is necessary (see table 1). However, with the exception of iodised salt, their success in developing countries has been mixed (Underwood; United Nations ACC/SCN; Cook, Skikne, and Baynes).

Biofortification is a new approach that complements the existing "toolbox" of interventions. It refers to breeding staple food crops – which form the mainstay of the diet for large numbers of at-risk people – for higher micronutrient levels. Thus the strategy is targeted at those who cannot afford a diet adequate in fruits, vegetables and meats, which are better sources of micronutrients. In principle, once such micronutrient-rich crops are developed and successfully disseminated, they automatically form part of the food chain. Hence, for a largely one-time investment this strategy can produce a constant stream of future benefits to consumers of these crops. Moreover, consumer acceptance of crops that are biofortified with iron and zinc, which are largely invisible traits, is not expected to be an issue. A comparison of the potential advantages of biofortification, relative to the other interventions, is contained in table 1. So far, there has been no systematic attempt to analyse the benefits and costs of this strategy; the present article attempts to do so.

In particular, this article attempts to quantify the extent to which the biofortification strategy can help ameliorate ID. Since iron-rich wheat and rice varieties are still being developed and have not yet been disseminated, the quantification necessarily is *ex ante* in nature. We employ the "disability adjusted life years" (DALYs) framework, which gained currency as metric for measuring health outcomes. In departure from the received literature, however, this study models explicitly the *functional* consequences of ID. The focus of this article is on India, a country that is home to many of those suffering from micronutrient malnutrition. ID is the single largest micronutrient deficiency in India; about 50% of women are anaemic, as are 74% of children (IIPS).[1]

The following sections sets out the DALYs methodology, highlight the extensions and modifications to the way this framework is utilised, present estimates of the burden of ID in India, consider the potential reduction in this burden under 2 scenarios, quantify the cost-effectiveness of biofortification, provide results of cost-benefit analyses, and compare these results with those of other interventions.

Measuring health

Since the 1990s, with the "World Development Report" (World Bank) and with "The Global Burden of Disease" study (GBD) by Murray and Lopez, DALYs have become increasingly popular to measure health: they are used not only to establish the burden of a disease in a particular region, but also more generally as a yardstick to capture and quantify a range of adverse effects on human life and health that have such different causes as communicable diseases (Mills and Shillcutt), sanitation and hygiene risks (Rijsberman), malnutrition (Behrman, Alderman, and Hoddinott) or civil war (Collier and Hoeffler). Quantifying the burden of vitamin A deficiency in the Philippines, Zimmermann and Qaim were the first to employ this framework to analyse the benefits of biofortification.

Compared to other measures that are used to value health interventions, such as cost-of-illness or willingness-to-pay approaches, DALYs do not rely on the financial capacity or the economic potential of the affected individuals; health is not valued differently for different individuals. Rather, it is quantified according to the severity of the health outcomes in question and expressed in common units that combine both morbidity and premature mortality. This standardisation allows comparisons across different health outcomes. The crucial element in this measure is the weighting of years of life lived with disabilities resulting from a specific disease; these severity weights (or "disability weights") can be in the range between 0 and 1, with 0 representing perfect health and 1 representing a health status equal to death. Because DALYs capture the whole scope of a disease the approach also circumvents the shortcomings of proxy-measures, like mortality, which might attract the attention of policy makers but divert resources from non-fatal but more widespread health problems.

The DALYs measure of the total burden of a disease is obtained as the sum of "years of life lost" (YLL) due to cause-specific mortality and the sum of "years lived with disability" (YLD), the latter of which are weighted (Murray and Lopez). That is,

(1) $\textit{Burden of disease} = DALYs_{lost} = YLL + YLD$, where

(2) $YLL = f\,(\textit{size of target group, mortality rate of disease, discount rate})$, and

(3) $YLD = f\,(\textit{size of target group, incidence rate, disability weight, discount rate})$.

Taking account of potentially different incidence rates and levels of severity of a disease between different groups within a population, and following Zimmermann and Qaim, the complete formula can be represented more formally as:

$$DALYs_{lost} = \sum_j T_j M_{ij} \left(\frac{1 - e^{-rL_j}}{r} \right) + \sum_i \sum_j T_j I_{ij} D_{ij} \left(\frac{1 - e^{-rd_{ij}}}{r} \right) \tag{4}$$

where T_j is the total number of people in target group j and M_{ij} is the mortality rate associated with the given disease i. I_{ij} is the incidence rate of disease i that is of interest, D_{ij} is the corresponding disability weight, and d_{ij} is the duration of the disease. For permanent disabilities d_{ij} equals the average remaining life expectancy L_j. Future life is discounted at the rate of r.

Applying this formula to analyse a disease or its sequelae yields the (current) burden of disease; interventions that change one of the components of the formula (in particular the incidence and mortality rates) result in a different (potential/future) burden of disease. The difference in DALYs between the current burden ("without" intervention) and the future burden ("with" intervention) then gives the health impact of the intervention in common units, i.e. "DALYs saved".

For this article, as a first step, the adverse health consequences of ID need to be specified. ID is defined in relation to body iron stores and haemoglobin concentrations; in its more severe manifestations it can take the form of iron deficiency anaemia (IDA). IDA is a subgroup of anaemia, which can also have other causes, like hookworms or malaria (Nestel and Davidsson). Anaemia can be classified as "mild", "moderate", and "severe". The GBD uses moderate and severe IDA and, in addition, "cognitive impairment" in its calculation of DALYs. In our approach, we go beyond this classification and specify the burden of IDA on a "deeper" level, i.e., on the level of the actual functional outcomes that can be attributed to IDA. These are (i) impaired physical activity (Hallberg and Scrimshaw), (ii) impaired mental development (Nokes and Bundy), and (iii) maternal mortality, which leads to further negative outcomes such as increases in the number of stillbirths and child deaths that occur due to the lack of breastfeeding and care caused by the death of the mother (Rush).

There is no robust scientific evidence that ID is linked to tangible adverse functional outcomes up to a state of moderate IDA (Rush, Stoltzfus). Therefore we only calculate DALYs for functional outcomes that can be attributed to moderate or severe IDA. We did not include any other adverse functional outcome, for which there is no scientific consensus on the link between the disease and ID.[2] This means that the results derived from this exercise represent a lower bound of the burden of ID.

The calculation of DALYs for impaired physical activity is carried out for moderate and severe manifestations and differentiated between the group of children under five, the group of children aged 6-14 years, the group of men and the group of women, to take account of different prevalence rates. DALYs for impaired mental development (for which permanent effects are assumed) are calculated for children under five and differentiated according to moderate and severe manifestations. DALYs that are lost due to maternal mortality are based on the number of live births. Disability weights (DA-weights) were discussed by the experts within the group of authors and based on those used by Murray and Lopez in the GBD (table 2).

Before employing the DALYs method detailed above to quantify ID in India, it is important to recognise – and in some cases address – some of the criticisms made of this approach. The formula laid out differs from the "original" formula used by Murray in that it omits "age-weighting", which acts to increase the burden of a disease if the disabling condition affects young, productive adults (as opposed to infants or the elderly). However, this implies an ethical value judgement, a social preference for certain age groups, and has been the subject of criticism (e.g., Anand and Hanson, Lyttkens, Richardson 1999a, Williams). Other literature suggests that including social preferences based on personal characteristics could be justified, whether it is for utility or for equity reasons (Olsen et al.). Murray justifies the inclusion of an age-weighting term indeed by referring to studies on the social and individual willingness-to-pay for health care, which give more weight to the contribution of young adults to (social and emotional) welfare. If this argument were to be followed further, it could imply, for instance, that the life and health of a physician or a celebrity would have a higher value than the life of, say, an unskilled labourer or an orphan, thus “opening a Pandora’s box” (Lyttkens). Therefore, in this analysis we exclude age-weighting. Note, however, that even so age plays a significant role in the calculations: saving the life of a child prevents the loss of more DALYs than saving the life of an older person, because of the longer remaining life expectancy.

Another component of the DALYs calculations in the GBD, which has attracted criticism for its arbitrariness and for introducing a gender bias, was the assumed remaining life expectancy (Lyttkens). As the GBD intends to capture the burden of *all* diseases simultaneously, there is the need to assume a maximum “biological” life expectancy to be able to calculate the remaining (hypothetical) life expectancy in the absence of any disease or fatal incident. Murray based this maximum theoretical life expectancy on the life expectancy of Japanese women, as this is the highest observed life expectancy in the world; men’s theoretical life expectancy was then put at a somewhat lower age because of “biological differences”. In effect, this amounts to introducing a “sex weight”, which implies that, *ceteris paribus*, interventions aimed at saving the lives of women save more DALYs. We use a standard life table for India (WHO 2001). This may be justified on grounds that changes in the prevalence of a single condition – in this case ID – are not expected to change average life expectancy significantly (Williams).

The DA-weights used to calculate DALYs have also attracted criticism on various grounds (Anand and Hanson; Lyttkens; Allotey et al.; Groce, Chamie, and Me; Richardson 1999b). These include: whether health experts are "better" able to determine these weights than members of the public; the assumed independence of the DA-weights regarding the context in which the disabling condition occurs;[3] and the apparent systematic bias against the permanently disabled. While such issues will likely continue to remain contentious, in this article, in determining the DA-weights for functional outcomes related to ID, the context of developing countries was very clearly at the forefront. Furthermore, this article does not separately consider the health state of individuals (permanently disabled or healthy) in calculating the YLL.

Another criticism of the DALYs formula is the discounting of future life years (Richardson 1999a; Lyttkens; Anand and Hanson). If future life years are discounted, present lives become relatively more valuable; this can serve to justify interventions that benefit the present generation at the expense of future generations. If the measurement of ill health becomes dependent on time the same illness causes a bigger loss of DALYs today than it does tomorrow. In short, discounting is deemed inequitable. Murray and Richardson (1999a) contain good overviews of these and related issues (such as opportunity costs and the time paradox). We support the view that discounting of health benefits makes sense and follow the World Bank and Murray and apply a 3% discount rate in our calculations. However, given the sensitivity of the results to the choice of a discount rate, we also report a second set of results in table 9, which has been calculated without discounting of health benefits. Note that if the objective is to rank alternative interventions, then discounting does not matter: if an intervention decreases a given burden of a disease by a certain percentage, then, for all practical purposes, the result will not change for different discount rates, as these are applied to both the with and without intervention alternatives.

Another criticism of the DALY approach is that it focuses only on the health of affected individuals, but fails to take account of health care costs, of private care by relatives and friends, or of the anxiety of people close those affected (Lyttkens). Furthermore, DALYs can be seen to value human life – whether implicitly or explicitly – and to express the value of life simply as a positive function of health, thus failing to capture all dimensions of life, while at the same time passing over positive contributions of the ill and disabled and opening the doors for their exclusion (Arnesen and Nord; Groce, Chamie, and Me).

Yet, all measures of ill health suffer from one limitation or another. For instance, the cost-of-illness approach focuses on health care costs and lost productivity only and, hence, attaches more value to richer or more productive individuals. DALYs – though not free of limitations despite our modifications – capture the burden of a disease in a transparent and more equitable manner.

The burden of iron deficiency in India

The starting point for quantifying the burden of ID is information on the prevalence of anaemia. For India, anaemia prevalence rates are taken from current literature (IIPS and NIN) and, following Stein et al., transformed into incidence rates for IDA for the target groups used in this study (table 4). For maternal mortality it was assumed that 5% of total maternal mortality, which was also taken from IIPS, is due to IDA.[4] The group sizes, i.e. the number of people in the target groups, are based on Census of India data (online at www.censusindia.net). The average remaining life expectancies used are taken from an Indian life table (WHO 2001).

Applying these data to the DALY framework yields the current burden of ID in India: an annual loss of 4m healthy life years (3.7m of which are lost through morbidity and 240,000 are lost due to mortality). Even though ID is already an acknowledged public health problem in India, this figure underlines the severity of this deficiency.

Calculating the impact of biofortification

By increasing the iron content of rice and wheat, biofortification is expected to increase iron intakes, and thereby to decrease the prevalence of ID and IDA. However, before making an assessment of the likely impact of an intervention such as biofortification, it is useful to review dietary patterns in India: cereal consumption in India is high; it averaged 12.7 kg per capita per month (pcpm) in rural areas, and 10.4 kg pcpm in urban areas. Rice and wheat constitute the bulk of the cereals consumed: in rural areas rice consumption averaged 6.8 kg pcpm and that of wheat averaged 4.5 kg pcpm (India 2001). This is why in this study the focus is on rice and wheat. Yet, there are distinct geographical patterns in dietary intakes: in some regions rice predominates, in others wheat does, and in yet others both are consumed. This is summarised in figure 1, which illustrates the composition of cereal consumption by state in rural areas. Hence, for our analysis we disaggregated India into three dietary regions. As source for information on food consumption, we used a nationally-representative household survey (India 1999/2000). This survey covered over 100,000 households in both rural and urban areas, and canvassed information on over 140 individual food items. Individual-specific intakes are, however, not covered and must be imputed. By using the unit record data from these surveys, it is possible to use food composition tables (Gopalan, Rama Sastri, and Balasubramanian) to derive the corresponding nutrient intakes.[5]

Given this background, biofortifying rice and wheat can be expected to contribute significantly to increased iron intakes. However, iron-rich crops are not yet out on the farmers' fields and on the consumers' plates. Therefore any assessment of a potential impact of such an intervention must necessarily be *ex-ante* in nature. It also depends critically on the assumptions made, *inter alia,* about the likely micronutrient content of the new wheat and rice varieties, and their acceptance by farmers and consumers. These are indicated in table 3, under both optimistic and pessimistic scenarios, so as to capture the range of possible outcomes. The scenarios reflect the expert input of breeders, agronomists, agricultural economists and other scientist at the centres of the Consultative Group on International Agricultural Research (CGIAR), who are working on biofortification research.[6]

According this information, an increase in iron content of 100-167% for rice compared to current varieties is deemed to be a reasonable assumption; for wheat the assumed range is 20-60%. As the additional iron will be bred into the biofortified varieties by means of non-transgenic methods, the iron compounds will be the same as in existing varieties and there is no reason to assume that the bioavailability of this additional iron changes; it is simply more of the same. For the coming years it is assumed that the "iron trait" will be bred into more and more varieties and the estimates of the experts indicate that after 20 years iron-rich rice can reach a share of 20-50% in total rice production and iron-rich wheat can reach a share of 30-50% in total wheat production.[7]

Note that the biofortification strategy explicitly involves breeding nutrient-dense *and* agronomically-superior varieties to facilitate adoption among farmers. As these are expected to be developed in collaboration with national agricultural research systems as part of ongoing research efforts, seed prices should be unaffected and hence not be a deterrent to adoption. Furthermore, given that iron-rich rice and wheat would look and taste no different from the present varieties, consumer acceptance should be easy as well. Based on these assumptions the iron intake in the "with biofortification"-scenario can be computed as follows:

(5) new iron intake = total current iron intake +

*+ (current iron intake from crop * percentage increase in iron * production share[8])*

To relate the new (higher) iron intakes to functional outcomes, a further step is necessary. One advantage of using unit record data is the possibility to rank intakes from lowest to highest and to obtain the cut-off intake level (by inversion) that corresponds to the prevalence rates for IDA; any individual with an iron intake below the cut-off level is assumed to suffer from the corresponding disease. As illustrated in figure 2, which sets out a hypothetical cumulative distribution function for iron intakes, higher intakes imply a shifting out to the right of the distribution of intakes. A new, "with biofortification" prevalence rate can then be inferred by determining the percentage of people with intakes below the cut-off. The new rate for maternal mortality is derived from the old rate by applying the percent decrease stated for severe IDA amongst women. Given these new figures, the number of DALYs lost can be recomputed to determine the remaining burden of ID. Note that this approach, which utilises information from a representative household survey, enables a more precise estimate of the likely impact than would be possible with the use of average consumption data and an assumed "dose response" function, as is done in the aforementioned study by Zimmermann and Qaim on vitamin A deficiency.

For implementing this method, it is necessary to determine iron intakes by individual members of the household. As noted above, the data we use contains only household-level information. We make the assumption that the food available per household may be attributed to its individual members based on their relative energy requirements; that is, we established calorie-based adult equivalents. The reasoning is that staples contribute to the bulk of calories, and that food is distributed according to the energy requirements of household members (rather than according to their iron requirements).[9] The results of this exercise yield the new prevalence rates of IDA (table 4). The respective new burdens of ID and the differences to the *status quo* are indicated in table 5.[10]

Even under pessimistic assumptions biofortification of both rice and wheat could save 1.4m healthy life years every year. The remaining burden of ID would then amount to an annual loss of 2.6m DALYs. In this case 36% of the current burden of ID would be eliminated. In the optimistic scenario the remaining burden of ID for India would be only 0.9m DALYs lost per year. This amounts to a decrease of the current burden of ID of 77%, which represents 3.1m healthy life years that could be saved each year.[11]

The cost-effectiveness of biofortification

One of the advantages of biofortification is the absence of major recurrent costs, compared to interventions like industrial fortification or pharmaceutical supplementation (table 10). Nevertheless, there are initial costs for research and basic breeding efforts for the development of the first iron-rich lines; there are marginal costs for testing, for adaptive breeding, for dissemination and, to a lesser extent, for extension activities.[12] And there are also some continuous marginal costs for maintenance breeding to preserve the iron-rich trait. As the basic R&D undertaken is not specifically focused on India alone, the resulting iron-rich varieties can be adopted by many more countries and yield benefits there. However, as this analysis is to establish the costs and benefits of an intervention that is not yet being used, limiting the potential scope and attributing all costs to the current main target countries (India, Bangladesh and the Philippines for rice and India and Pakistan for wheat) seems to be a conservative approach.[13]

Based on information of the breeders of the CGIAR centres and on the budget in the biofortification programme proposal of CIAT and IFPRI, we established a pessimistic and an optimistic scenario for the time frame and costs of biofortification of rice and wheat (table 6). Under the pessimistic assumptions the present cost is US$ 17.3m for both crops together; the average annual discounted cost amounts to US$ 0.6m, descending from US$ 1m in the base year to US$ 0.4m in the last year considered. In the optimistic scenario the present value of total costs equals US$ 8m and the average present costs per year amount to US$ 0.3m, descending from US$ 0.5m in the base year to US$ 0.2m in the last year considered.[14]

Having established the relevant costs that would need to be spent on development, release and dissemination of iron-rich rice and wheat, the cost-effectiveness of this new nutrition intervention can be determined. In the pessimistic scenario 9.1m DALYs in present terms can be saved, while discounted costs equal a net present value of US$ 17.3m. Hence, even in the pessimistic scenario the current "price" of saving one healthy life year through iron biofortification of both rice and wheat is not even 2 Dollars, namely US$ 1.90. In the optimistic scenario 22.1m DALYs in present terms can be saved through biofortification, while the net present cost amounts only to US$ 8m. In this case the "price" of saving one DALY is only US$ 0.36, i.e. if invested in iron biofortification of rice and wheat in India, saving one healthy life year costs only 36 Cents (table 7).

To put these results into a context: in its World Development Report 1993, the World Bank describes costs per DALY saved of about US$ 1 to US$ 3 as "most cost-effective" (p. 63). In fact, the report portrays costs of saving one DALY for less than US$ 25 as "remarkably low", and includes activities as "highly cost-effective" that cost between US$ 50 and US$ 150 per DALY gained (p. 8). Given this yardstick, iron biofortification of rice and wheat proves to be a very cost-effective intervention; even under pessimistic assumptions it ranks before all but one of the 47 interventions analysed in the World Development Report. Gillespie gives a more specific overview of the cost-effectiveness of micronutrient interventions in general and of ID control programmes in particular; he quotes figures of US$ 4.4 to US$ 12.8 per DALY saved for iron fortification and supplementation programmes respectively. Compared to the cost-effectiveness of these other interventions, saving healthy life years through iron biofortification is clearly a very “cheap” approach. The results without discounting of health benefits are even more favourable (table 9).[15]

Monetising benefits of biofortification

The discussion so far has accounted for the benefits in terms of the number of healthy life years saved. Indeed, avoiding a reliance on money to measure health benefits is the very “beauty” of the DALY concept as it circumvents the ethically dubious exercise of attaching a monetary value to human life. However, there are pragmatic reasons to ascribe a monetary value to benefits as well as to costs. The most significant of these is the need to compare biofortification with other strategies to combat IDA, which often use financial indicators. It needs scarcely to be stressed that attaching a monetary value to a healthy life year does not entail the intention to determine the intrinsic value of life as such. Choosing a value that should be attached to a DALY is a rather arbitrary exercise for which there exists no consensus in the literature.[16] We use both US$ 500, which is close to India’s per capita income, and US$ 1,000 to convert the number of DALYs saved into monetary benefits. Using standard values also facilitates the comparison of our results across different countries.

Carrying out a CBA of iron biofortification of both rice and wheat under the pessimistic assumptions and using a DALY value of US$ 500 gives a benefit-cost ratio (BCR) of 264 and an internal rate of return (IRR) of 74%; in the optimistic scenario the IRR is even 152%. An overview of these figures, including the results for iron biofortification of rice or wheat on their own, and including results for using a DALY value of US$ of 1,000 instead of US$ 500, is given in table 8. (The results without discounting of health benefits are given in table 9.) These results show clearly that the potential rates of return on investments in iron biofortification in the context of India are huge. And this is the case even when a DALY is assigned a value of only US$ 500 – a value that certainly fails to account for many, if not most, dimensions of health, human happiness and well-being.

It is useful to compare these results with those of other interventions. One early analysis of iron fortification and supplementation (Levin) focused on quantifiable benefits like productivity only. He concluded that industrial fortification is advantageous because it requires little effort by the target groups and is cheap; BCRs calculated for different scenarios and for different developing countries ranged from 5-79 for fortification and from 1.6-59 for supplementation. In a more recent overview of micronutrient interventions, Behrman, Alderman and Hoddinott give BCRs of 176-200 for iron fortification and of 6.1-14 for supplementation. Looking at the economics of ID in 10 different developing countries, Horton and Ross find a BCR for iron fortification programmes of 6-36. However, they only look at the economic impact of increased productivity and not at the more fundamental health benefits *per se*. Analysing micronutrient programmes in different Asian countries, with one exception Horton finds BCRs of 3.6-10.3 for iron supplementation. Looking at the efficacy of food-based interventions – albeit not biofortification – to reduce ID in India, Weinberger (2002) underlines their cost-effectiveness when she explains that due to the large number of iron deficient people in India it can be expected that food-based approaches to improve their iron status will yield good results at a relatively low cost per person. An analysis that focuses specifically on iron biofortification in

India (and Bangladesh) can be found in Bouis: a given monetary value is attached per case of anaemia averted and, disregarding potential agricultural benefits, in sum juxtaposed to the expected costs. The resulting BCRs are in the range of 19-79, and the IRRs range from 29-44%.

Conclusions

In this article it has become clear that there are already different possible interventions to combat micronutrient malnutrition, all of which have their particular strengths, and many of which are considered to be cost-effective. Our goal has been to analyse the cost-effectiveness of a new tool, biofortification, which we did for iron biofortification of rice and wheat in India. To measure the potential impact of iron biofortification, we refined the methodology of "disability-adjusted life years" (DALYs) to quantify potential health benefits of iron-rich rice and wheat, thus analysing an aspect of agricultural technology that has so far received little attention: the potential role of plant-breeding in fighting micronutrient malnutrition. In doing so we did not only widen the reach of agricultural economics to encompass another dimension of health and food security, we also provided a knowledge base on which decision makers can build their assessment of this novel micronutrient intervention.

Often health interventions are evaluated based on the economic power and the financial capacities of the individuals reached. This has certain ethical limitations. Contrary to these methods, the DALY approach does not rely on monetary terms to quantify human life and health; it captures the more comprehensive impact of diseases on the ability of people to realise their physical and psychological potential. According to our calculations, the current burden of iron deficiency (ID) in India amounts to 4m healthy life years lost each year. We showed that biofortification, even in a pessimistic scenario, can reduce the burden of ID on the Indian population by more than one third. In an optimistic scenario this burden would be reduced by more than 75%. Our analysis also showed that iron biofortification of rice and wheat is not only effective in reducing the burden of ID, but also cost-effective compared to other health interventions. (This cost-effectiveness can mainly be explained by the continuous benefit stream that follows the development of biofortified rice and wheat, and by the absence of major recurrent costs.) In our pessimistic scenario each 1.90 U.S. Dollars invested in the biofortification programme save one healthy life year. In the optimistic scenario the cost of one DALY is even lower: saving a healthy life year only costs 36 Cents. Extending this analysis – for pragmatic and advocacy reason – to a cost-benefit analysis, the results are just as impressive. In the pessimistic scenario we derived an internal rate of return of 74%, while in the optimistic scenario this figure even reached 152%. Comparing our results with other studies on micronutrient interventions, iron biofortification outperforms alternatives with regard to cost-effectiveness and financial indicators.

The strategy of breeding for micronutrient-dense staple crops is not supposed to solve the problem of micronutrient malnutrition for good – the overarching goal is certainly to improve and diversify the diets of the poor, if not to lift them out of poverty altogether. However, until this long-term objective is reached, this study suggests that iron biofortification represents an economically viable intermediate intervention to improve life, health and well-being of millions of people around the globe; there is little doubt that investment into biofortification and related research has enormous potential far beyond India. With fixed costs for basic R&D, each country where ID is a public health problem and where the population eats sufficient quantities of the crop in question only needs to fund and carry out adaptive breeding and dissemination to reap health benefits for its population for years to come. In this case the assumption is, of course, that the germplasm of biofortified crops is in the public domain. Given that biofortification research is currently being carried out at the CGIAR centres this is a likely and promising perspective. Yet, benefits will only materialise if biofortified crops are actually eaten by poor consumers and peasant farmers.

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Tables and figures

Table 1. Characteristics of Alternative Micronutrient Interventions

	Biofortification	**Industrial fortification**	**Food-based approaches**	**Supplementation**
Dose	low	low	low	high
Indication	prevention	prevention	prevention	targeted prevention, treatment
Potential coverage	wide (consumers of staple food crops)	wide (consumers of processed foodstuff)	narrow (participants in promotion progr.)	narrow (recipients of supplements)
Targeting	general	general (urban)	regional focal points (rural)	risk populations (urban)
Infrastructure	seed distribution systems	food marketing channels	extension and education system	health system
Agents	research institutes	food processors	extension workers	health workers
Funding time frame	one-time R&D, some continuous	continuous	long-term	continuous
Funding source	public/donors	public (subsidies) or private (prices)	public/donors	public/donors
Monitoring	none	of food processors	none	of implementation
Intrusion	none (usual diet)*	none (usual diet)	yes (change of diet and customs)	some (compliance in taking pills)

* In certain instances biofortification may imply a switch from white to orange-fleshed crops.

Table 2. Disability Weights used

Diseases / functional outcomes	Target groups	DA-weights
Impaired physical activity from severe IDA (sIDA)	children ≤ 5 years, and 6-14 years	0.087
	women 15+ years, and men 15+ years	0.09
Impaired physical activity from moderate IDA (mIDA)	all	0.011
Impaired mental development from sIDA	children ≤ 5 years	0.024
Impaired mental development from mIDA	children ≤ 5 years	0.006

Table 3. Assumptions used in the Pessimistic and Optimistic Scenarios

	Iron-rich rice		**Iron-rich wheat**	
	Pessimistic scenario	**Optimistic scenario**	**Pessimistic scenario**	**Optimistic scenario**
Iron content in grain	3 ppm (after polishing)		38 ppm	
Potential iron content	6 ppm	8 ppm	46 ppm	61 ppm
Increase in iron content	100%	167%	20%	60%
Bioavailability	Unchanged			
Share in production 20 years after release	20%	50%	30%	50%

Table 4. Prevalence of IDA with and without Biofortification of Rice and Wheat

Selected target groups	Current prevalence rates of IDA		New prevalence rates of IDA			
			Pessimistic scenario		Optimistic scenario	
	Moderate	Severe	Moderate	Severe	Moderate	Severe
children ≤ 5 years	27.5%	3.2%	23.0%	1.4%	11.0%	0.3%
women ≥ 15 years	7.4%	1.0%	5.3%	0.3%	1.2%	0.1%

Table 5. Burden of Iron Deficiency and Potential Gains with Biofortification

Biofortification of	Scenario	DALYs saved	Decrease relative to *status quo**	Remaining burden of ID (DALYs)
Rice & wheat	pessimistic	1.4 m	-36%	2.6 m
Rice & wheat	optimistic	3.1 m	-77%	0.9 m
Rice	pessimistic	1.2 m	-29%	2.8 m
Rice	optimistic	2.3 m	-59%	1.7 m
Wheat	pessimistic	0.3 m	-8%	3.6 m
Wheat	optimistic	1.1 m	-27%	2.9 m

* In the *status quo* 4m DALYs are lost.

Table 6. Assumptions used for the Cost and Time Structure of Biofortification R&D

	Iron-rich rice		**Iron-rich wheat**	
	Pessimistic scenario	**Optimistic scenario**	**Pessimistic scenario**	**Optimistic scenario**
Basic R&D costs per year	US$ 0.44 m	US$ 0.22 m	US$ 0.55 m	US$ 0.28 m
Duration of basic R&D	8 years	6 years	9 years	7 years
Country-specific costs per year	US$ 0.8 m	US$ 0.5 m	US$ 0.8 m	US$ 0.5 m
Duration of in-country activities	5 years	3 years	7 years	5 years
Maintenance costs per year, until end of the 30 year period considered	US$ 0.2 m	US$ 0.1 m	US$ 0.2 m	US$ 0.1 m

Sources: Budget of CIAT and IFPRI, information from breeders and own assumptions.

Table 7. Cost-Effectiveness of Iron Biofortification of Rice and Wheat

		Iron biofortification of	
	both rice & wheat	**only rice**	**only wheat**
	US$ per DALY	US$ per DALY	US$ per DALY
Pessimistic scenario	1.90	1.05	4.86
Optimistic scenario	0.36	0.21	0.62

Table 8. Internal Rates of Return and Benefit-Cost Ratios for Iron Biofortification

		Iron biofortification of					
		Rice & wheat		Rice		Wheat	
		IRR	BCR	IRR	BCR	IRR	BCR
1 DALY = US$ 500	Pessimistic scenario	74%	264	86%	477	52%	103
	Optimistic scenario	152%	1379	173%	2404	111%	804
1 DALY = US$ 1,000	Pessimistic scenario	88%	527	100%	953	62%	206
	Optimistic scenario	180%	2759	204%	4808	131%	1608

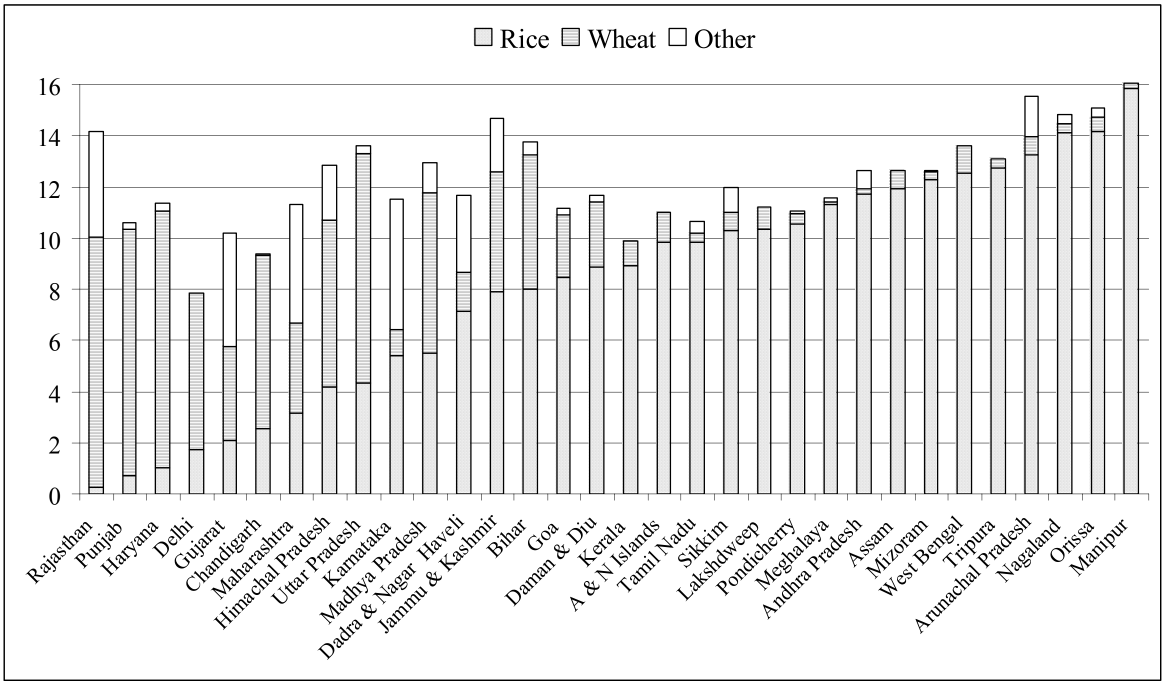
Table 9. Results with and without Discounting of Health Benefits

Iron biofortification of rice and wheat	**With discounting of health benefits**		**Without discounting of health benefits**	
	pessimistic	optimistic	pessimistic	optimistic
Loss in *status quo*	4.0 m DALYs		7.3 m DALYs	
Loss with biofortification	2.6 m DALYs	0.9 m DALYs	4.7 m DALYs	1.7 m DALYs
DALYs gained	1.4 m DALYs	3.1 m DALYs	2.6 m DALYs	5.5 m DALYs
Reduction of burden of ID	-36 percent	-77 percent	-35 percent	-76 percent
Cost per DALY	US$ 1.90	US$ 0.36	US$ 0.54	US$ 0.15
Internal rate of return	74 percent	152 percent	86 percent	176 percent

Table 10. Imputed Costs for India's Anaemia Control Programme (Tablets only)

Target group	Size of target group	Target coverage	Dose	Cost per 100 tablets*	Total costs (46 Rs./US$)
Pregnant women w/o severe IDA	27.4m	50%	100 big tablets/case	5.45 Rs.	US$ 1.6m
Pregnant women with severe IDA	0.57m	50%	200 big tablets/case	5.45 Rs.	US$ 0.07m
Children aged 1-5 (incl.)	127.6m	50%	100 small tablets/year	2.5 Rs.	US$ 3.5m
	Hypothetical annual costs for iron and folic acid tablets				**US$ 5.2m**

* U. Kapil (2004, personal communication).



Source: Underlying data taken from India (1999/2000), state-wise disaggregation.

Figure 1. Cereal Consumption (kg/capita/month) in Rural India, 1999/2000

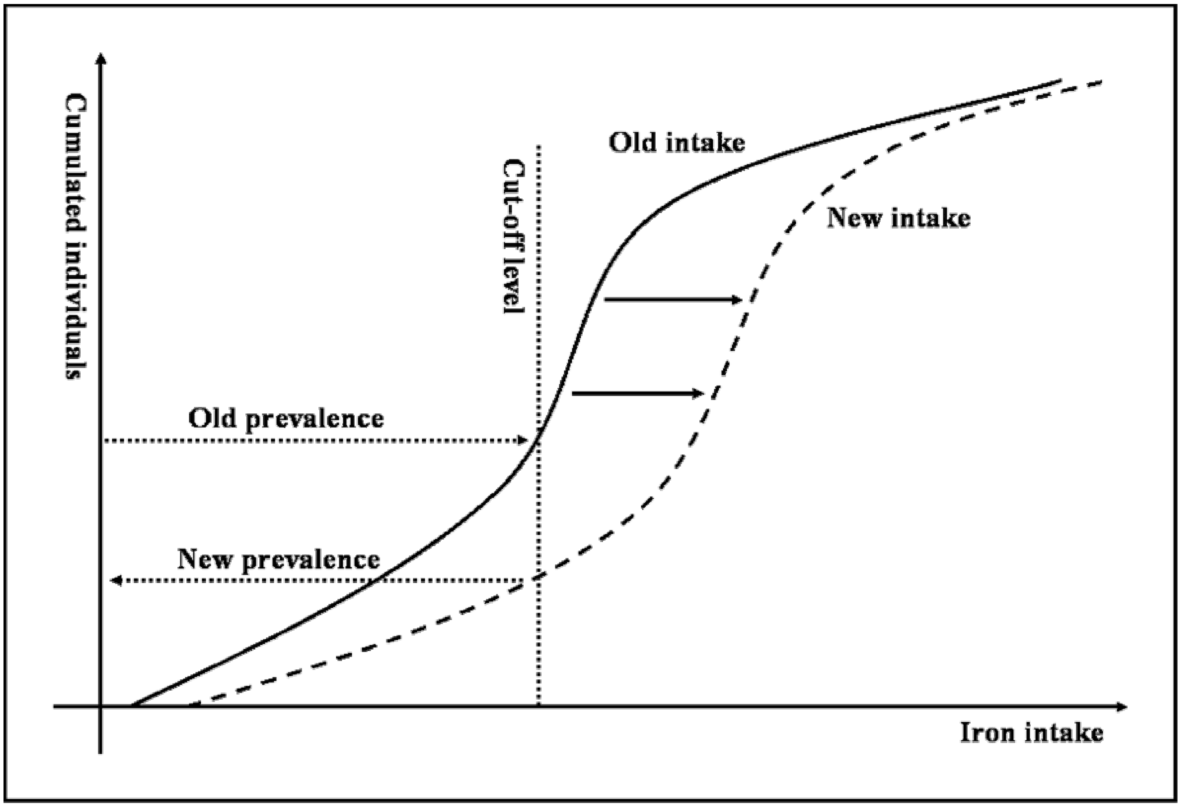


Figure 2. Deriving prevalence rates from intake data

Endnotes

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[1] The aetiology of anaemia is multifactorial; however, from a public health perspective ID is believed to be the most important causal factor. In the absence of other cheap and simple, yet valid, indicators, anaemia is used as a surrogate to estimate the burden of this deficiency. Consequently often the expressions anaemia, iron deficiency anaemia and iron deficiency are used interchangeably. Nevertheless, it is important to be aware that these 3 terms represent different entities since every case of anaemia is not due to ID and every iron deficient subject is not anaemic.

[2] For example, although certain studies suggest that stunting might be a functional outcome of ID (e.g, Soewondo, Husaini, and Pollitt; Latham et al.), a recent meta-analysis could not establish a significant cause-effect relationship (Ramakrishnan et al.), which is why we did not include stunting.

[3] Allotey et al. give an illustrative account of this criticism, comparing the lives of people suffering from paraplegia in different places (rural Cameroon and urban Australia).

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[4] These 5% are an assumption that was made, because for maternal mortality there are only observational data for mortality associated with severe anaemia and not with ID.

[5] We are grateful to R. Sharma for providing us with her computations of iron intakes at the unit record level (unpublished PhD dissertation, Delhi School of Economics). These data have been modified to take account of the possibility of contamination iron in the food composition values used. For example, in the case of milled rice a value of 3 ppm iron is used (G. Barry and P. Virk, personal communication, 2005).

[6] The centres involved are the International Rice Research Institute (IRRI) and the Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT). The additional expert input was obtained from G. Barry, P. Virk, G. Gregorio and J. Rickman of IRRI and from I. Ortiz Monasterio and E. Meng of CIMMYT.

[7] There is also a positive probability that, given the complexities of the underlying genetics and the *ex ante* nature of the analysis, plant breeders will be unable to achieve these nutrient levels within the assumed time span. This analysis does not take account of this source of uncertainty as the results would be trivial.

[8] The assumption is that the coverage rates of biofortified rice and wheat translate into production shares, which determine the share of biofortified and non-biofortified crops in the individual consumption: because they are not distinguishable, iron-rich varieties are assumed to mingle freely with "old" varieties on the market. (Producer-consumers are also expected to change only gradually and not fully to the new varieties.)

[9] The results with this set of adult equivalents proved to be very robust when we used adult equivalents that were derived in a regression from the data set itself. In this regression the iron intake of the household was the dependent variable and the information on household composition (age and gender groups) provided the independent variables. Note, however, that because energy and iron requirements differ it is well possible (and even likely) that some members within the same household are iron deficient while others are not: for example for men, with their relatively low iron requirements, it is easier to cover their iron requirements with their relatively big share of food than it is for women.

[10] It is useful to comment on the difference between biofortifying one crop, rather than both: Even though there are rice-eating and wheat-eating regions, households consume both cereals to some extent. Therefore, if biofortification of one crop already results in iron sufficiency for an individual, biofortifying the other crop will not have an additional benefit. Adding up the results for separate biofortification of either rice or wheat will lead to double counting and overestimate the potential impact of a combined biofortification

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programme. Nevertheless, looking at the potential impact of biofortifying one crop only can be enlightening, which is why we also report results for stand-alone biofortification efforts.

[11] India has also a long-standing programme to provide iron and folic acid supplements to young children and pregnant women. However, it is generally acknowledged that it has little real impact. It is considered to be insufficiently administered, underfunded, and suffering from infrastructure problems and poor compliance (Kapil; Vijayaraghavan; Kapil, Saxena, and Nayar). Therefore we do not expect this programme to have an impact that would significantly distort our calculations.

[12] Marginal costs in this context are the costs that have to be incurred to develop and promote the iron-rich trait in addition to regular breeding and dissemination costs. Of course the money spent on these activities will also influence the ultimate coverage rate of the iron-rich varieties. Yet, in our pessimistic scenario we assume higher dissemination and extension costs but a lower adoption rate, while in the optimistic scenario we assume lower costs but a higher adoption rate. But these two approaches are only meant to mark the very limits of the potential benefits and costs of biofortification.

[13] Based on FAOSTAT data (http://faostat.fao.org/faostat/), if the production shares of all developing countries in Asia in the respective crops were used as basis to attribute the R&D costs at the international level, India's share would sink from 70.5 to 23.2% for rice and from 78.5 to 31.7% for wheat.

[14] In comparison, the annual costs only for the iron and folic acid tablets of India's iron supplementation programme (see Endnote 11), with its limited scope and target coverage, would amount to US$ 5.2m if the programme was completely implemented (Table 10).

[15] Another way to look at the costs of biofortification is to attribute costs on a per capita basis. In the pessimistic scenario this is US$ 0.0006 per capita only and in the optimistic scenario it is US$ 0.0003.

[16] Recent studies that used DALYs in the context of developing countries resorted to standardised rates of US$ 1000 or US$ 500 per DALY; in other cases the economic potential of the country was used as basis and a DALY was valued at per capita income (Collier and Hoeffler; Rijsberman; Mills and Shillcutt; Behrman, Alderman, and Hoddinott; Appleton; and Zimmermann and Qaim).