

Plant breeding to control zinc deficiency in India: how cost-effective is biofortification?

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Abstract

Objective: To estimate the potential impact of zinc biofortification of rice and wheat on public health in India and to evaluate its cost-effectiveness compared with alternative interventions and international standards.

Design: The burden of zinc deficiency (ZnD) in India was expressed in disability-adjusted life years (DALYs) lost. Current zinc intakes were derived from a nationally representative household food consumption survey (30-day recall) and attributed to household members based on adult equivalent weights. Using a dose–response function, projected increased zinc intakes from biofortified rice and wheat were translated into potential health improvements for pessimistic and optimistic scenarios. After estimating the costs of developing and disseminating the new varieties, the cost-effectiveness of zinc biofortification was calculated for both scenarios and compared with alternative micronutrient interventions and international reference standards.

Setting: India.

Subjects: Representative household survey ($n = 119\,554$).

Results: The calculated annual burden of ZnD in India is 2.8 million DALYs lost. Zinc biofortification of rice and wheat may reduce this burden by 20–51% and save 0.6–1.4 million DALYs each year, depending on the scenario. The cost for saving one DALY amounts to \$US 0.73–7.31, which is very cost-effective by standards of the World Bank and the World Health Organization, and is lower than that of most other micronutrient interventions.

Conclusions: Not only may zinc biofortification save lives and prevent morbidity among millions of people, it may also help accommodate the need to economise and to allocate resources more efficiently. Further research is needed to corroborate these findings.

Keywords
 Micronutrient malnutrition
 Biofortification
 Plant breeding
 Zinc-rich staple crops
 Zinc deficiency
 Health benefits
 Disability-adjusted life years
 Cost-effectiveness
 India

Adequate intake of nutritious foods is a prerequisite to achieving and maintaining good health and well-being. Millions of people worldwide, however, are unable to achieve this. An estimated 852 million people do not eat sufficient food to meet their energy requirements and are consequently undernourished. Many more people suffer from 'hidden hunger': 150 million are vitamin-A-deficient, almost 2 billion are iodine-deficient, between 4 and 5 billion are iron-deficient¹ and about 2.7 billion are zinc-deficient². This imbalance between 'overt' and 'hidden' hunger is underlined in the report of the United Nations Millennium Project's Task Force on Hunger³, where the authors call for further investments in agriculture and confirm the major role that agricultural research has played in reducing hunger. Indeed, the advent of the Green Revolution in the 1960s – in which high-yielding

crop varieties were introduced and combined with more intense use of inputs, such as irrigation and agrochemicals – was instrumental in increasing the food supply in developing countries. The general concern today is less about whether there is sufficient food in the world, but rather how to distribute and ensure access for those in need without compromising their independence, self-reliance and dignity.†

Historically, the control of micronutrient malnutrition has been under the domain of public health, rather than agriculture, despite the same underlying cause: an

†This is not to say that the Green Revolution did not have its shortcomings and weaknesses. By solving some problems new ones were created – not least a shift in the consumption patterns of the poor towards cheap but monotonous cereal-based diets⁴.

inadequate intake of a balanced diet. This was because clinical deficiencies were widespread and control was driven by the medical model that focused on the provision of therapeutic and preventive pharmaceutical supplements, such as iron or iron–folate tablets to pregnant women or of vitamin A capsules to older infants and young children. More recently food fortification has come to the fore: for example, salt iodisation; flour fortification with iron; and fortification of sugar and cooking oil with vitamin A.

Pharmaceutical supplementation and food fortification gained acceptance as viable options once it was deemed they were very cost-effective^{2,5–7}. Yet, as with all interventions, impact depends on coverage. The further the programme is from urban centres and the more it targets people at the margin of society, the more difficult and expensive it is to increase coverage². Rural people, and to a certain extent the urban poor, tend to eat less processed food; thus they are often not reached by food fortification programmes, especially where both the food industry and food market infrastructure are immature. Likewise, a weak health infrastructure coupled with discrimination can limit the effectiveness and efficiency of pharmaceutical supplementation programmes. Moreover, both fortification and supplementation programmes require financial commitment year on year, either directly by the government or donors, or indirectly through voluntary measures (e.g. donated labour/time or absorbing the marginal cost of fortification) or higher prices for fortified foodstuffs. Monitoring the fortificant levels in food or the coverage of either programme imposes additional administrative burdens.

Because micronutrient malnutrition is the consequence of a lack of access to adequate quality food and the existing interventions are not easy to implement in all areas, a new initiative was started recently in which food quality is recognised as an important agricultural objective. The means to fulfil this objective includes breeding crops – notably staple foods – both for higher yields and higher micronutrient content, an approach known as ‘biofortification’^{8,9}. This approach has multiple advantages, including the fact that it capitalises on the regular daily intake of a consistent amount of food staple by all family members, and, because staple foods predominate in the diets of the poor, this strategy implicitly targets low-income households¹⁰. Biofortification also provides a feasible means of reaching micronutrient-deficient populations in relatively remote rural areas. (For example, subsequent to the introduction of modern wheat varieties to India in the mid-1960s, adoption rates exceeded 70% within 10 years¹¹.) Thus biofortification can deliver naturally fortified foods to people with limited access to commercially marketed fortified foods that are more readily available in urban areas¹⁰. Because farmers will not adopt new crops unless they provide an agronomic and/or economic advantage, the strategy is to introduce high zinc content as a standard trait for releases of new varieties (that have desirable

agronomic properties) or to introduce the zinc-rich trait into new releases of popular varieties. As such, there will be only marginal costs for distribution and marketing.

Zinc deficiency (ZnD) is one of the five leading risk factors that contribute to the burden of disease in developing countries with high mortality rates². Despite this, the extent and severity of ZnD have not received the attention given to others, notably iodine, iron and vitamin A^{12,13}, largely because of the difficulty in measuring zinc status. With a better understanding of the consequences of ZnD and the development of proxy indicators for deficiency, concerted efforts are now being made to control ZnD. One of these is to breed crops for higher zinc content, a goal of the HarvestPlus programme.*

To provide a common framework for estimating the effectiveness† and cost-effectiveness of zinc biofortification, and to compare biofortification with conventional fortification and pharmaceutical supplementation programmes, Stein *et al.*¹⁴ developed a model based on disability-adjusted life years (DALYs). This model can be used to measure both the current burden of ZnD and the likely impact of biofortification, and it also enables economic analyses of the related costs and benefits. The present paper reports the outcome of the first application of this framework, to the introduction of zinc-rich wheat and zinc-rich rice in India to control ZnD. Because the specific varieties are still at the stage of research and development (R&D), the analysis is necessarily carried out as an *ex-ante* study.

The International Zinc Nutrition Consultative Group¹² estimates that 26% of the Indian population is at risk of inadequate zinc intakes. Clearly ZnD in India is a public health problem that warrants a detailed analysis, and the present paper starts with this. It then goes on to show the potential impact of zinc biofortification on the burden of ZnD in India. The focus is on wheat and rice given that India is divided into predominantly wheat-eating and rice-eating states (Fig. 1¹⁵).

A ‘recommended action’ of the World Health Report² is that ‘cost-effectiveness analyses should be used to identify high, medium and low priority interventions to prevent or reduce risks, with highest priority given to those interventions that are cost-effective and affordable’ (p.11). Therefore, in the third and final step, the cost-effectiveness of zinc biofortification is analysed. The latter is significant because biofortification is proposed as a complementary intervention to conventional fortification and preventive pharmaceutical supplementation; thus it is important to know whether biofortification uses scarce resources as efficiently as the existing interventions.

*HarvestPlus is the biofortification programme of the Consultative Group on International Agricultural Research that was started in 2004. The programme focuses on iron, zinc and β -carotene.

†Here, effectiveness is based on the efficaciousness of zinc interventions coupled with projected coverage.

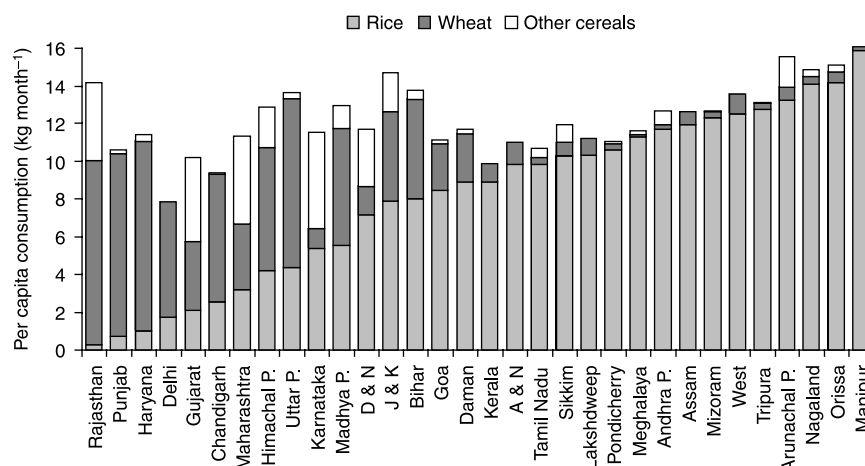


Fig. 1 Average per capita consumption of cereals (kg month⁻¹) in rural India, per state, 1999/2000¹⁵ (P. – Pradesh; D & N – Dadra and Nagar; J & K – Jammu and Kashmir)

Methods

The burden of ZnD in India was quantified using the DALY method, in which morbidity is assigned a weight and combined with information on mortality to give a common measure of ill health^{14,16,17}. Four per cent of all under-fives mortality can be prevented if all children have sufficient intakes of absorbable zinc¹⁸. The known adverse health outcomes from ZnD that do not necessarily result in death are diarrhoea^{19,20}, pneumonia²¹ and stunting²². The target groups for these conditions included both infants (below 1 year of age) and children (1–5 years of age). The incidence rates, disability weights and durations used for each condition are shown in Table 1^{14,23,24}. To derive the remaining life expectancy in the case of child mortality and for duration of stunting, which was considered a permanent condition, standard life tables for India were used²⁵. The size of the target groups were taken from Census of India data^{26,27}.

The 55th survey of the Indian National Sample Survey Organisation¹⁵ – which is a representative survey that included 120 000 households – was used to compute zinc intakes. Household-level data on the quantities and volumes of the foodstuffs and beverages consumed in the preceding month were multiplied by their respective zinc content using Indian food composition tables²⁸. * For the few foods for which national composition values were not available, the corresponding zinc values in the US food

*The survey not only recorded food expenditure but also the *amounts* of over 140 different foodstuffs consumed by the household over a 30-day recall period. According to the survey codebook¹⁵, the instructions for the interviewers were to include all consumption of monetary and non-monetary purchases and goods received, as well as all household consumption from livestock keeping (like milk, meat or eggs) and consumption from transfer receipts. Hence, household consumption comprises (1) commodities purchased in cash, (2) commodities received in exchange of goods and services, (3) home-grown/home-produced stock, (4) transfer receipts such as gifts, loans, charities, etc. and (5) free collection.

composition table were used²⁹; given the small number of less important food items concerned, a potential bias because of underlying differences in the zinc content of the soil is expected to be insignificant. The survey data for household composition and the energy requirements of Indians²⁸ in different age and gender groups were used to compute the zinc intake per adult equivalent in each household (i.e. the assumption is that there is no general, nationwide and persistent bias in the distribution of food within the households^{30,31}). The estimated zinc intake of individual household members was then calculated as a proportion of the adult equivalent.

Future consumption of biofortified wheat and rice will lead to higher zinc intakes and reduce the incidence of deficiency-related health conditions. To anticipate changes in zinc intakes, the food composition values of zinc for wheat and rice were replaced with the assumed increases in zinc contents through biofortification; the latter were used to derive projected zinc intakes. As neither biofortified wheat nor biofortified rice has been released, the projected increases in zinc contents were estimated by the plant breeders at the International Rice Research Institute and the International Maize and Wheat Improvement Centre based on the variation in zinc concentrations found in the germplasm screening. The plant breeders and other experts also estimated potential coverage rates for both crops 20 years after release (Fig. 2). Because of the multiple sources of uncertainty arising from these estimations, an optimistic–pessimistic scenario approach was chosen (Table 2) to increase the reliability of the results³²; for the potential coverage rate, a further sensitivity analysis was carried out to determine the lowest bound at which zinc biofortification can still be considered cost-effective.

Current zinc intakes together with the potential zinc intakes from biofortified wheat and rice (which were simulated based on the food consumption data, the food composition information and the expected zinc content in wheat and rice; Table 2) and the estimated average

Table 1 Data used to calculate disability-adjusted life years lost due to ZnD in India

Health outcome related to ZnD	Target group	Incidence rate*	Disability weight†	Duration of disease	Age of death/onset of disease
Diarrhoea	Infants	0.468	0.2	3 days	N/A
	Children	0.234	0.15	4 days	N/A
Pneumonia	Infants	0.119	0.3	4 days	N/A
	Children	0.119	0.2	4 days	N/A
Stunting Mortality	Infants	0.455‡	0.0001	Rest of life	6 months
	Children	0.0027§	N/A	N/A	8 months
		0.001§	N/A	N/A	2 years

ZnD – zinc deficiency; N/A – not applicable.

* Fraction of target group that experiences the health outcome.

† Extent of disability that is caused by the health outcome (perfect health corresponds to a weight of 0, death to a weight of 1).

Source: reference 14, ‡reference 23, §reference 24.

requirements for zinc for individuals consuming unrefined, cereal-based diets¹² were used to calculate separate efficacy ratios at the individual level for both scenarios. These efficacy ratios are based on the notion that a given absolute increase in zinc intake will have a bigger impact on the health of a very deficient individual than on the health of an almost sufficient individual: the more deficient a person is, the higher the efficacy of a given increment in zinc intake¹⁴. To calculate new incidence and mortality rates, mean efficacy ratios were derived for the target groups. These new rates were used to recalculate the burden of ZnD in India with biofortification for the two scenarios. The difference to the number of DALYs lost in the status quo is the impact of biofortification.

Finally, the number of DALYs that could be saved through biofortification was juxtaposed on the costs of biofortifying wheat and rice to determine the cost-effectiveness of the intervention. The costs for the optimistic scenario were derived from the HarvestPlus budget³³ as the development of the new varieties is being funded through this programme; for the pessimistic scenarios these figures were doubled, making this a conservative assumption. The expected time required for R&D was estimated by the lead plant breeders (G Barry and I Ortiz-Monasterio, personal communication, December 2004) (Table 3). The time horizon of the analyses was set at 30 years, which is a common time frame for economic analyses because after that time discounting levels the impact of future events. In the present context, it also covers the life cycle of the biofortified crops from the initial R&D until the maximum assumed coverage of these crops (Fig. 2). To discount future costs and benefits to the base year, a 3% rate was used¹⁴. R&D costs were attributed to the main target countries according to their respective production shares.* Potentially, other countries can also

*For wheat the main target countries are India and Pakistan; for rice the main target countries are India, Bangladesh and the Philippines. In the optimistic scenario the costs were moreover shared amongst secondary target countries (China, Indonesia and Vietnam for rice, and China for wheat).

benefit from biofortified wheat or rice, but costs tend to be underestimated *ex-ante*. This warrants a cautious approach when projecting costs into the future. Also, the actual adoption of biofortified varieties is still an open issue.

Results

The current burden of ZnD in India amounts to 2.8 million DALYs lost, 2.7 million from mortality and 140 000 from morbidity, 70% of which occurs among infants (Fig. 3). With zinc biofortification of wheat and rice 0.6 million DALYs can be saved each year in the pessimistic scenario, while 1.4 million DALYs can be gained annually under the optimistic assumptions. This corresponds to a reduction of the burden of ZnD of 20 and 51%, respectively (Table 4). Yet, while the biggest burden of ZnD is borne by infants, the biggest health gain through biofortification occurs among children aged 1–5 years (Fig. 4). If these health benefits are set against the costs to be incurred for zinc biofortification of wheat and rice for India, and if all values are discounted to the base year, saving one healthy life year through biofortification costs \$US 7.31 under the pessimistic assumptions or as little as \$US 0.73 in the optimistic scenario.

Expressed in mortality figures only, the annual burden of ZnD in India is 95 500 deaths; with zinc biofortification 18 350 and 48 100 lives can be saved in the pessimistic and optimistic scenario, respectively. Juxtaposing the net present cost and the (undiscounted) number of infant and child deaths that can be averted within the 30-year time frame yields a cost of \$US 115 per life saved in the pessimistic scenario, while under optimistic assumptions saving one life through zinc biofortification costs only \$US 12 (Table 5).

Discussion

The results show that ZnD imposes a heavy burden on public health in India, most of it due to mortality associated with impaired immune function and thus greater susceptibility to infectious diseases. With 2.8 million DALYs lost each year, the burden is lower than the burden of 4 million DALYs lost in India due to

Year		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Pessimistic scenario	Activities	Basic R&D								Country-specific activities*								Maintenance breeding													
	Coverage(%)	0	0	0	0	0	0	0	0	0	...	3	..	6	...	9	...	12	...	15	...	18	...	21	...	24	...	27	...	30	30
Optimistic scenario	Activities	Basic R&D								Country-specific act.*								Maintenance breeding													
	Coverage(%)	0	0	0	0	0	0	0	...	5	...	10	..	15	...	20	...	25	...	30	...	35	...	40	...	45	..	50	50	50	50

Fig. 2 The time frame and adoption rates for the analysis of zinc biofortification (for the example of zinc-rich wheat). *The assumption is that some of the advanced lines released by the International Rice Research Institute and the International Maize and Wheat Improvement Centre are suitable for immediate cultivation in India. Additional biofortified varieties are then released in the course of the country-specific activities. It is also assumed that the varieties with the biggest potential coverage are adapted first. Also see Tables 2 and 3 (R&D – research and development; act. – activities)

Table 2 Assumptions about the success of zinc biofortification of wheat and rice

	Wheat*		Rice†	
	Pessimistic scenario	Optimistic scenario	Pessimistic scenario	Optimistic scenario
Current zinc content (ppm)	31 for whole-wheat flour		13 for milled rice	
Potential zinc content (ppm)	37	55	24	35
Potential increase (%)	20	77	85	169
Potential coverage rate (%)	30	50	20	50

PPM – parts per million.
 Source: *I Ortiz-Monasterio and †G Barry (personal communication, 2006).

Table 3 Assumptions about costs of zinc biofortification of wheat and rice

	Wheat		Rice	
	Pessimistic scenario	Optimistic scenario	Pessimistic scenario	Optimistic scenario
Average annual costs (\$US million)				
Basic R&D (screening, breeding, testing, release of advanced line)	1.4	0.7	1.6	0.8
Country-specific activities (adaptive breeding, dissemination, extension)	0.8	0.5	0.8	0.5
Maintenance breeding	0.2	0.1	0.2	0.1
Duration (years)				
Basic R&D	9	7	8	6
Country-specific activities	7	5	5	3
Maintenance breeding	Until end of 30-years period			

R&D – research and development.
 Source: Based on reference 32, I Ortiz-Monasterio and G Barry (personal communication, 2004).

iron-deficiency anaemia³⁴, but it still poses a problem of a considerable magnitude.* ZnD has received little public attention, and no systematic interventions are currently in place to control this micronutrient deficiency³⁵. This analysis shows that zinc biofortification of wheat and rice in India may be an effective means to reduce the burden of ZnD. Given the higher natural zinc content in existing wheat varieties and the lower potential increases in biofortified wheat compared with rice, the impact of wheat biofortification is lower than the impact of rice biofortification. Nevertheless, by biofortifying not only rice but also wheat, it may be possible to reduce the burden of ZnD by an additional 2–10%, i.e. by 60 000–290 000 DALYs.† The impact of zinc biofortification is not completely additive, because if both crops are biofortified some consumers might already achieve sufficiency with the consumption of one crop only and hence biofortification of the other crop does not bring any additional benefit to these individuals.

A limitation of this analysis is the use of household-level rather than individual-level food intake data, because nationally representative food intake data are not currently

*While the burden of *mortality* is bigger for ZnD than for iron-deficiency anaemia (IDA), the burden of *morbidity* is bigger for IDA than for ZnD simply because many more people are affected by IDA. (Because DALYs capture both mortality and morbidity they are a more appropriate measure of ill health than mortality rates.)

†Another, future possibility could be to biofortify rice and wheat not only with zinc but also with iron to address multiple micronutrient deficiencies simultaneously.

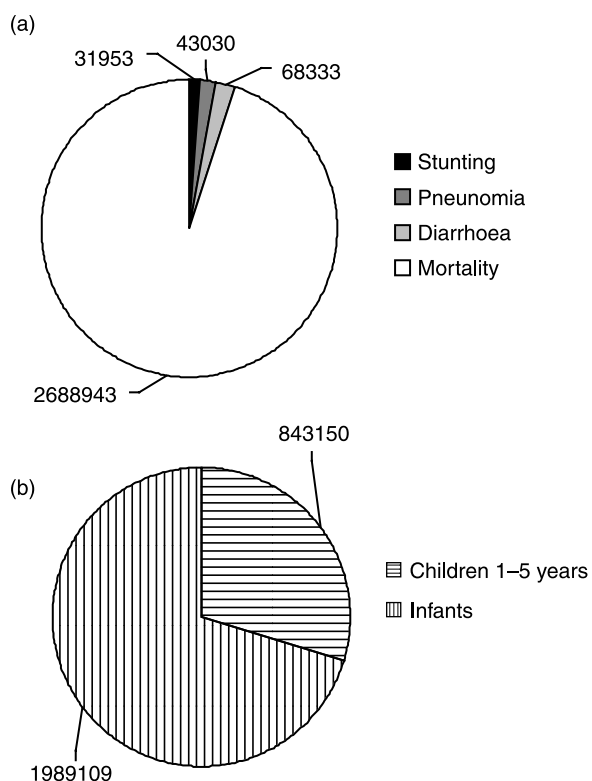


Fig. 3 Number of disability-adjusted life years (DALYs) lost due to the different health outcomes of zinc deficiency (a) and number of DALYs lost by the two target groups (b)

Table 4 Potential impact of zinc biofortification on the burden of ZnD in India

Crop	Scenario	DALYs lost due to ZnD	DALYs gained relative to status quo	Reduction of burden of ZnD (%)
Wheat	Status quo	2 830 000	N/A	N/A
	Pessimistic	2 770 000	60 000	2
	Optimistic	2 510 000	330 000	12
Rice	Pessimistic	2 330 000	500 000	18
	Optimistic	1 670 000	1 160 000	41
Wheat and rice	Pessimistic	2 270 000	560 000	20
	Optimistic	1 390 000	1 450 000	51

ZnD – zinc deficiency; DALY – disability-adjusted life year; N/A – not applicable.

available. Consequently, the use of adult equivalent weights to attribute a share of the household's overall consumption to each household member only approximates actual individual intakes, and may significantly overestimate infant intakes. However, if maternal zinc status can be improved through (long-term) consumption of zinc-biofortified rice and wheat, it is plausible that the status of her newborn infant will be better than it otherwise would be; consequently, infants may be less at-risk of succumbing to morbidity due to infectious diseases. Our approach is already a notable improvement over previous work (for vitamin A deficiency) that used highly aggregated national average consumption data as the basis for projecting the potential impact of a biofortified crop¹⁷. It is also an improvement over the use of national food balance data to assess population zinc status³⁶, which are production-based and reflect average nutrient availability at the national level only – i.e. the use of household data and adult equivalent weights allows for estimating intakes at a more disaggregated level. Clearly further research with better data is necessary to corroborate the findings. None the less, the approach used here provides important preliminary findings for policy-makers and researchers, and can be regarded as a useful and interesting starting point for further studies.

Showing that an intervention can work (i.e. its efficacy) and quantifying its potential benefits (i.e. in this case the number of healthy life years that can be saved) is necessary, but only a first step. Where resources are limited and funding is scarce, an intervention also needs to

be cost-effective compared with alternatives. Scarcity needs to be managed, and in public health such management is paramount. The World Development Report (WDR)⁵ underlines that 'because interventions can differ so much in cost-effectiveness, making allocative decisions badly in either the public or the private sectors costs lives' (p.61). This is also why DALYs were introduced as a unit for measuring health effects: to be able to compare different interventions by what it costs to achieve an additional year of healthy life. The WDR provided a 'yardstick' for assessing the cost-effectiveness of public health initiatives by indicating that saving one DALY for less than \$US 150 is highly cost-effective. In another publication the World Bank⁶ states that most micronutrient programmes cost less than \$US 50 per DALY saved, with iron fortification, iodine fortification and vitamin A supplementation to children under the age of 5 years costing \$US 4, \$US 8 and \$US 9 per DALY saved, respectively. A recent assessment of (hypothetical) zinc fortification in Southeast Asia reports a cost of international \$ 14 per DALY averted³⁷.* The World Health Organization's (WHO) Commission on Macroeconomics and Health³⁸ classified DALY values equal to average per capita income as conservative assumptions and propagated the use of three times the per capita income to value one DALY. The Indian per capita income in 2004 was \$US 620³⁹; hence, according to the WHO, health interventions in India can already be considered cost-effective if they save a DALY at a cost of less than \$US 1860.

Given that the above yardsticks originate from different years, the issue of inflationary adjustment becomes relevant before any comparisons can be made between the present study and these sources. To convert the nominal \$US values given in the sources cited above into real terms, the inflation calculator of the US Bureau of Labor Statistics (<http://www.bls.gov/cpi>) was used, which is based on the average consumer price index for a given calendar year. 2004 was selected as base year. The resulting new reference values – expressed in constant

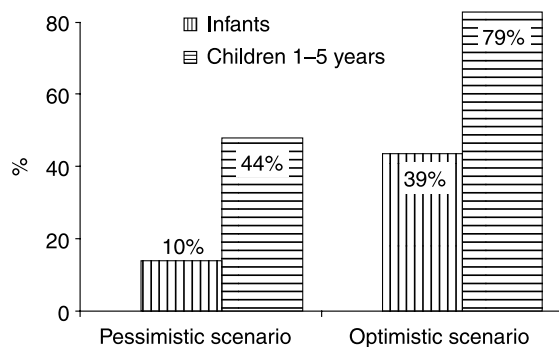


Fig. 4 The reduction of the burden of zinc deficiency through biofortification by age group

*Here methodological differences in calculating a 'DALY' are disregarded. Yet, it is not expected that these differences would change the magnitudes of the results in a relevant manner.

Table 5 Cost-effectiveness of zinc biofortification of wheat and rice over 30 years

Crop	Scenario	Net present cost per DALY saved (\$US)	IRR* (%)	Net present cost per life saved (\$US)	Average annual cost per citizen (\$US)
Wheat	Pessimistic	39.45	31	1194.03	0.0004
	Optimistic	1.98	98	59.70	0.0001
Rice	Pessimistic	3.90	66	119.37	0.0004
	Optimistic	0.40	173	12.03	0.0001
Wheat and rice	Pessimistic	7.31	56	115.04	0.0009
	Optimistic	0.73	150	11.62	0.0003

DALY – disability-adjusted life year.

* Internal rate of return (if one DALY is valued at \$US 1000).

Table 6 DALY values and thresholds for cost-effectiveness of health interventions

	Cost (\$US) per DALY saved (respective years)	Cost (\$US) per DALY saved (constant 2004)*
Threshold derived from the WHO's conventional valuation of one DALY ³⁴		1860
Threshold derived from the WHO's conservative valuation of one DALY ³⁴		620
Threshold of the World Bank for high cost-effectiveness of public health initiatives ⁵	150	217
Actual costs per DALY saved for different micronutrient interventions ⁶	4–9	5.8–13.0
Cost effectiveness of zinc fortification in Southeast Asia with 95% coverage ³⁷	14†	15.4†
Estimated cost per DALY saved through zinc biofortification		0.7–7.3

DALY – disability-adjusted life year; WHO – World Health Organization.

* Source: consumer price index of the US Bureau of Labor Statistics (<http://www.bls.gov/cpi>).

† These figures are expressed in international \$; therefore the cost-effectiveness ratios are relatively higher than those expressed in \$US.

terms – are reported in Table 6. Against this background the imputed costs of \$US 0.73–7.31 for saving one DALY through zinc biofortification of wheat and zinc (Table 5) is extremely low: compared with both other micronutrient interventions and the standards set by the World Bank and the WHO, zinc biofortification may be very cost-effective.*

In this study DALYs were used to measure the loss of health, but looking at mortality alone can provide a compelling argument for zinc biofortification of wheat and rice: deaths of infants and children can be averted for as little as \$US 12–115 per case (Table 5). Another perspective can be gained if the costs of zinc biofortification over 30 years are disaggregated to the per capita level: zinc biofortification would cost only \$US 0.0003–0.0009 per citizen in India per year (Table 5). The transition from a cost-effectiveness analysis – or a cost-utility analysis – to a cost-benefit analysis allows for the intervention to be

*If the assumed coverage rate for wheat and rice in the pessimistic scenario (of 30 and 20%, respectively) is reduced further – to determine a switching value for this key assumption – it can be shown that with a coverage rate of only 0.25% for both crops, saving one DALY costs \$US 210, i.e. still less than the World Bank's threshold of \$US 217. With such a low coverage rate the actual objective of addressing ZnD comprehensively would certainly not be achieved. But the robust results on the cost-effectiveness of zinc biofortification show that the risk of a misinvestment of R&D resources is very low.

assessed not only in terms of its technical efficiency but also in terms of its allocative efficiency in a context that goes beyond the health sector⁴⁰. In a similar analysis for the Philippines, Zimmermann and Qaim¹⁷ reported internal rates of return (IRRs) of 66–133% for 'Golden Rice',* which is intended to control vitamin A deficiency. However, they used the annual per capita income of the Philippines of \$US 1030 in 2000 to value a DALY. With a somewhat lower but otherwise better comparable DALY value of \$US 1000¹⁴, the IRRs for zinc biofortification in India are 56–150%.

Conclusion

This study has shown that ZnD, with an annual loss of 2.8 million healthy life years, can be considered a public health problem in India. Zinc biofortification of wheat and rice may reduce this burden by 20–51%, saving the lives of 18 350 or even 48 100 children. At the same time zinc biofortification has the potential to be a very cost-effective intervention by any standard: saving one healthy life year is expected to cost as little as \$US 0.73–7.31 if both wheat and rice can be bred for higher zinc concentrations.

*'Golden Rice' is rice that is biofortified with β -carotene, hence acquiring a yellow-golden hue.

Yet, given these promising results, we concur with the World Health Report²: 'It is not much value to provide decision-makers with information on the costs and effectiveness of interventions that are undertaken badly. Accordingly, the results reported here show what would be achieved if the interventions were undertaken in a relatively efficient manner' (p.107). This is particularly true for the country-specific adaptive breeding efforts and adoption rates; even if HarvestPlus can provide advanced lines of zinc-rich wheat and rice, these varieties will need to reach as many farmers and consumers as soon as possible. Here we have demonstrated what the *potential* benefits may be to Indian society – based on reasonable assumptions. However, for these benefits to materialise, the support and the collaboration of key players in the international donor community, national agricultural research and extension agencies and national health systems are needed to generate data on their bioefficacy and acceptability, thereby proving that biofortification is cost-effective where ZnD is a public health problem and where wheat and rice are eaten by large parts of the population.

By controlling a large proportion of ZnD through biofortification, scarce resources – in terms of manpower and money – can be targeted to both direct and indirect interventions to control severe deficiency. Hence biofortification may not only save lives and prevent morbidity among millions of people, it may also help accommodate the budgetary need to economise and to allocate resources more efficiently between different interventions – whether within the health sector or otherwise.

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