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The social and economic impact of biofortification through genetic modification

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Genetic modification (GM) has been advocated as an alternative or complement to micronutrient interventions such as supplementation, fortification or dietary diversification. While proof-of-concept of various GM biofortified crops looks promising, the decision tree of policy makers is much more complex, and requires insight on their socio-economic impacts: Will it actually work? Is it financially sound? Will people accept it? Can it be implemented in a globalized world? This review shows that GM biofortification could effectively reduce the burden of micronutrient deficiencies, in an economically viable way, and is generally well received by target beneficiaries, despite some resistance and uncertainty. Practically, however, protectionist and/or unscientific regulations in some developed countries raise the (perceived) bar for implementation in target countries.

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Introduction

Building upon more than two decades of related research, the proof-of-concept and potential impact on public health of *bio*fortification – that is, the enhancement of the nutrient content of crops as opposed to the addition of nutrients to food during processing – has been established for a variety of crops and micronutrients; in particular this can be achieved through conventional breeding (cross-breeding), genetic modification (GM), or the application of mineral fertilizer. Given the existing literature [1••,2••,3], here we focus on GM biofortification.

Evidence of the value of biofortification through conventional breeding (and related dissemination efforts) as a successful nutrition and public health intervention in South-East Asia, Sub-Saharan Africa and Latin America, is growing (for a progress report on conventional breeding efforts for biofortification, see Ref. [3]). This has been clearly acknowledged at the WHO/FAO Technical consultation on biofortification in April 2016 [4]), and further exemplified when the pioneers of provitamin A-enriched orange-fleshed sweet potato (OFSP) were given the 2016 World Food Prize for their long-standing work to deploy this staple crop to nearly two million African households. In the future, also the large-scale deployment of other conventionally bred varieties could increase.

When it comes to genetic engineering to increase the nutritional value of staple crops, while an increasing number of successful efforts have been undertaken [5••], no such crops have been introduced yet. Awaiting the first approval and release of provitamin A-rich 'Golden Rice' and other genetically modified (GM) biofortified crops, like multi-biofortified 'BioCassava' [6], researchers have nevertheless attempted to examine their economic value in various ways. This review focuses on evidence and key literature on health impacts and cost-effectiveness, willingness-to-pay (WTP) and trade impacts of these crops. As such, this overview complements new/ongoing reviews focusing on nutritional aspects [7].

Impact and cost-effectiveness

Biofortified crops are not ordinary consumer goods in that they do not satisfy an obvious want but rather a hidden health need. On the market place consumers may therefore not differentiate between non-biofortified and biofortified crops, or they may not be prepared to pay a higher price for biofortified crops. As such, biofortified crops (i) have an added nutrition dimension, which puts them into the realm of public health interventions; and (ii) they target food insecure and poor population groups in developing countries, which means their beneficiaries may not have sufficient purchasing power to create the demand needed for market actors to actually supply these crops, even if they are aware of their nutrition benefits.

Table 1

Potential impact and cost-effectiveness of GM biofortified crops (and alternative interventions or benchmarks reported in different studies)

	Biofortified crop (country)	Impact	Cost-effectiveness	Profitability
Dawe *et al.* [16]	Provitamin A 'Golden' Rice, 1st generation (Philippines)	VA intake increases by 2–8% of current intake	US$ 4–7 per million RAE provided (VA supplementation = US$ 30–73 per million RAE)	
Zimmermann and Qaim [10]	Provitamin A 'Golden' Rice, 1st generation (Philippines)	Burden of VAD decreases by 6–32%; 15 000–85 000 DALYs saved per year[a]		66–133% rate of return on R&D investments
Stein *et al.* [11•] Stein *et al.* [17]	Provitamin A 'Golden' Rice, 2nd generation (India)	Burden of VAD decreases by 9–59%; 204 000–1 382 000 DALYs saved per year	US$ 3–19 per DALY saved (other VA interventions = US$ 84–1860 per DALY saved)	29–93% rate of return (international agricultural R&D investments = 17–35%)
De Moura *et al.* [18]	Provitamin A 'Golden' Rice, 2nd generation (Bangladesh, Indonesia, Philippines)	Impact: prevalence of VAD decreases by 71–78% in Bangladesh and by 30–60% in Indonesia and the Philippines		
Changat and Krishna [19]	Protein-rich potato ('protato') (India)	Impact: protein content increases by up to a third, and levels of essential amino acids increase significantly; protein intake should increase and reduce the prevalence of PEM		
Krishna and Qaim [20]	Bt eggplant (India)[b]	Impact: consumers benefit from a technology-induced decrease in eggplant prices; since eggplant is an important vegetable in low-income households in India, this price decrease is pro-poor as positive nutritional effects can be expected from concomitant increases in vegetable consumption		
De Steur *et al.* [21]	Folate-enriched rice (China)	Impact: burden of folate deficiency decreases by 37–82%		
De Steur *et al.* [22]	Folate-enriched rice (China)	Burden of folate deficiency decreases by 20–60%	US$ 21–64 per DALY saved	
Chow *et al.* [23]	Provitamin A 'Golden Mustard' (India, rural areas of 16 (out of 29) states and 8 urban areas)	905 000–1 685 000 DALYs saved per year (expanding supplementation = 635 000–1 380 000 DALYs saved)	US$ 92–171 per DALY saved[c] (supplementation when fixed costs of expanding services are ignored = US $23–50 per DALY saved)	21–42% rate of return (supplementation = 68–104%, industrial fortification = 6–22%)
Henley *et al.* [24]	Transgenic biofortified sorghum (Sub-Saharan Africa)	Impact: PDCAAS doubles, while iron, zinc and provitamin A levels are expected to increase; young children should be able to meet most of their protein requirements from biofortified sorghum porridge		
Nguema *et al.* [25]	Multi-biofortified 'BioCassava' (Nigeria, Kenya)	Burden of VAD and iron deficiency decreases by 6% and 3% in Nigeria and Kenya, respectively	US$ 4–5 and US$ 56–87 per DALY saved in Nigeria and Kenya, respectively (other VA interventions in Africa = US$ 41–52 per DALY)	
De Steur *et al.* [26•]	Multi-biofortified rice (China)	Burden of VA, zinc, iron and folate deficiency decreases by 11–46%	US$ 2–10 per DALY saved	
Fiedler *et al.* [12]	High-provitamin A and high-iron banana (Uganda)	Burden of VAD and IDA decreases by 3–5%; 8600–12 900 DALYs saved per year	US$ 50–77 per DALY saved (World Bank benchmark = US$260 per DALY, WHO benchmark = US$1380 per DALY saved)	29–34% rate of return

Bt, *Bacillus thuringiensis*; VA, vitamin A (retinol); US$, United States dollar; RAE, retinol activity equivalents; VAD, VA deficiency; R&D, research and development; DALY, disability-adjusted life year; PEM, protein-energy malnutrition; PDCAAS, protein digestibility corrected amino acid score; IDA, iron deficiency anemia; WHO, World Health Organization.

[a] DALYs is a common metric used in public health research to quantify the burden of a disease, illness or injury in terms of life years that are lost due to premature mortality as well as to morbidity (in which case the severity of the condition is taken into account and the time spent with it is expressed as fractions of life years) [27,28•,29].

[b] Bt eggplant is a pest-resistant, first generation GM crop that is not a biofortified crop in the true sense, but it was included to show that other GM crops can have positive nutrition effects.

[c] The authors only report incremental cost-effectiveness, but for better comparability across the studies, we calculated the stand-alone cost-effectiveness of Golden Mustard.