



Biofortification: The Evidence

A summary of research that supports scaling up of biofortification to improve nutrition and health globally

HarvestPlus leads a global effort to develop and scale up micronutrient-rich staple food crops. The process used is known as biofortification: a cost-effective, sustainable solution that uses conventional plant breeding to increase the density of vitamins and minerals in staple crops consumed widely as part of everyday diets in Africa, Asia, and Latin America and the Caribbean. Micronutrients, although only required by the body in very small amounts, are essential to good health, cognition, and productivity.

Biofortification helps reduce the widespread gap between micronutrient requirements and intake by increasing the proportion of dietary vitamin A, iron, and zinc—three micronutrients of public health significance globally. Biofortified crops are particularly effective in delivering micronutrients to rural communities, where the majority of lower-income, small-holder farmers who produce staple food crops (and whose families' diets comprise mainly of such crops) reside, and where year-round diverse diets, commercially fortified foods or micronutrient supplements are often inaccessible. Women, young children and adolescent girls are the primary targets of biofortification because they have high nutrient needs that often go unmet. However, since staple foods are consumed widely by all household members, biofortification can provide profound health benefits to the whole family.

By the end of 2017, 6.7 million farming households were reached with biofortified planting material, benefiting about 33 million people, in 14 countries across Africa, Asia, and Latin America and the Caribbean. By 2020, HarvestPlus aims to reach 20 million farming households with biofortified planting material and, by 2030, one billion people are expected to consume biofortified foods globally. In the next five years, HarvestPlus aims to catalyze this scale up by investing in 30 priority countries selected based on their potential to pivot biofortification into the next big movement in food.

Efforts to scale up biofortification are supported by rigorous research and evidence, throughout the entire impact pathway of biofortification [1–4]. The *African Journal of Food, Agriculture, Nutrition, and Development* and the *Annals of the New York Academy of Sciences* recently devoted special issues to biofortification, which summarize the evidence landscape and suggest the way forward for this agricultural-nutrition intervention [5, 6].

HarvestPlus partners with crop breeding centers of the international agricultural research network known as the CGIAR to ensure conventionally bred varieties of nutritious, high-yielding and climate smart staple crops are developed and available for testing and released by national agricultural research systems (NARS). HarvestPlus and its partners measure the impact of biofortified crop consumption on women, adolescent girls and children's nutritional status and functional outcomes, such as cognitive and physical performance. Delivery progress, in outcomes such as adoption and diffusion, are captured through HarvestPlus' rigorous monitoring and evaluation system. Assessments of the effectiveness, cost-effectiveness, and impact of various delivery and promotion strategies are tested along staple crop value chains to share lessons learned and catalyze scale-up.

Over the last 15 years, research conducted by HarvestPlus and its partners has demonstrated that:

- Conventional crop breeding can increase nutrient levels without compromising yield
- Extra nutrients in crops measurably improve micronutrient status, health, and cognitive and physical abilities
- Farmers are willing to grow biofortified crops and consumers are willing to eat them
- Biofortification is cost-effective

Conventional crop breeding can increase nutrient levels without compromising yield

Plant breeders screen thousands of crop varieties stored in global seed banks to discover varieties with naturally higher amounts of essential micronutrients. Then, through collaborations with various breeding centers of the CGIAR, and NARS, these nutrient-rich varieties are used to breed biofortified varieties that are also high-yielding, disease and pest resistant, and climate smart in local agro-ecological conditions.

Planting material for biofortified crops are made available as public goods to national governments, who test and officially release the enriched varieties for planting in their country. Where they are sold by the private sector, they are competitively priced or included in subsidy schemes, so smallholder farmers can afford them.

Biofortified crops are bred to fulfill a biologically important portion of the dietary requirement of iron, zinc, or vitamin A of women and children, in populations where these crops are consumed as staples. Based on their usual eating patterns, it is estimated that for children 4 to 6 years old and for non-pregnant, non-lactating women of reproductive age, biofortification provides an additional 35 percent of the Estimated Average Requirement (EAR) of iron in beans and 40 percent in pearl millet; the additional zinc in wheat and rice provides up to 25 percent and 40 percent of the EAR, respectively; and, vitamin A in cassava, maize, and sweet potato provide > 50 percent of the EAR.

More than 290 varieties of 12 biofortified crops, including key staples such as iron beans, iron pearl millet, vitamin A cassava, vitamin A maize, vitamin A orange sweet potato (OSP), zinc maize, zinc rice and zinc wheat, have been officially released in over 30 countries. Thousands of varietal lines are currently in testing in these countries, and in over 30 more. As crop development research advances, the nutrient density of crops is further increased, and biofortified varieties are better adapted to the changing climate and consumer preferences.

Extra nutrients in crops improve health, micronutrient status, and cognitive abilities

Nutritionists measure the loss and retention of micronutrients in crops under traditional storage, processing and cooking conditions to be sure that sufficient levels of vitamins and minerals remain in foods that target populations typically eat [7–12]. Nutritionists also study the degree to which nutrients bred into crops are absorbed and utilized by the body, a prerequisite to improving micronutrient status [13]. Randomized controlled efficacy trials are used to demonstrate the impact of biofortified crops on nutritional status and functional indicators of micronutrient status (e.g. visual adaptation to darkness for vitamin A crops; memory, attention, and physical activity for iron crops; and growth and immune competence for zinc crops). Finally, randomized controlled effectiveness studies provide evidence that biofortified crops can improve the nutritional status of populations under typical (non-clinical) conditions.

As the case for biofortification builds, rigorous external reviews of the evidence are also taking place. For example, a recent systematic review of three randomized efficacy trials on iron-biofortified crops reinforced the conclusion that iron-biofortified interventions significantly improve iron status—particularly among women and children in low-income communities who need it most [14]. In addition, a World Health Organization (WHO) Cochrane review committee was assembled in 2016 to review the scientific evidence and country experiences of scaling up biofortification. Eight papers were published in the *Annals of the New York Academy of Science* as part of the consultation and a WHO recommendation on biofortification is expected in 2020.

Vitamin A orange sweet potato

Consumption of vitamin A OSP can result in a significant increase in body stores of vitamin A across age groups [15–17]. The primary evidence for the effectiveness of biofortification comes from vitamin A OSP, assessed through a randomized controlled effectiveness trial. The study reached 24,000 households in Uganda and Mozambique from 2006 to 2009, with vitamin A OSP adoption rates reaching over 60 percent among the beneficiaries. In Uganda, after four growing seasons, serum retinol increased significantly in children under five in the vitamin A OSP intervention group who had low vitamin A status at the beginning of the study [18]. In Mozambique, consumption of vitamin A OSP by children under five significantly reduced the burden of diarrhea, the second leading cause of death in this age group globally; the likelihood of experiencing diarrhea was reduced by 39 percent and duration of diarrhea episodes was reduced by more than 10 percent [19].

Vitamin A cassava

An efficacy study in Eastern Kenya with 5- to 13-year-old rural schoolchildren demonstrated modest but significant improvement in serum concentrations of retinol and beta-carotene in the vitamin A cassava versus the control group [20]. A recently completed efficacy trial with children under five in rural Nigeria aims to demonstrate the protective effect of vitamin A cassava on vitamin A status.

Vitamin A maize

An efficacy study in rural Zambia showed that after three months, total body stores of vitamin A in 5- to 6-year-old children eating vitamin A maize increased to a significant extent compared to control group [21]. A larger trial with over 1,000 marginally malnourished 4–8 year-old children in another farming district of Zambia demonstrated that vitamin A maize consumption significantly increased serum beta-carotene concentrations but did not improve serum retinol [22]; significant improvements in other carotenoids (α -carotene, β -cryptoxanthin, and zeaxanthin) were also detected, indicating the potential of vitamin A maize to effect health benefits beyond improvements in vitamin A status, such as protection from oxidative stress, chronic diseases, and age-related retinal degeneration [23]. In this same trial, visual adaptation to darkness was assessed: among children who were vitamin A deficient at baseline, those who consumed vitamin A maize had greater improvement in pupillary responsiveness than those in the control group, improving their ability to see in dim light [24]. Another shorter duration study in the same region showed no increase in mean breast milk retinol concentration among women who consumed vitamin A maize; however, the plausible downward trend in the risk of low milk retinol warrants further investigation [25].

Iron beans

Biofortified iron beans have been demonstrated to be efficacious in Rwanda, where iron-deficient university women experienced a significant increase in hemoglobin, ferritin, and total body iron after consuming biofortified beans for 4.5 months [26]. Iron beans had a profound effect on cognition: iron deficient women who ate biofortified beans experienced improved memory and ability to pay attention [27], key skills for optimal

performance at school and work. The study also measured physical performance and preliminary results suggest improvements in iron status were accompanied by a reduction in time spent in sedentary activity [28].

Iron pearl millet

Iron pearl millet was demonstrated to be an efficacious approach to improve iron status in adolescent children through a six-month study conducted in rural Maharashtra, India. After only four months, iron deficiency was significantly reduced, and serum ferritin and total body iron were significantly improved in secondary schoolchildren who consumed iron pearl millet flat bread twice daily. Children who were iron deficient at baseline were 64 percent more likely to resolve their deficiency by six months [29]. Recently published results from the same trial indicate that iron biofortified pearl millet consumption also improved cognitive performance [30].

Zinc rice

A zinc absorption trial is in progress in Bangladesh, where an efficacy study is also underway to determine the impact of biofortified zinc rice on the nutrition of young children aged 12–36 months. A previous study compared the absorption of zinc from an intrinsically labeled biofortified rice variety to commercially fortified rice in 16 healthy adults. The findings indicated that rice biofortification is as good a source of bioavailable zinc as postharvest zinc fortification [31].

Zinc wheat

An absorption study among women in Mexico showed that total absorbed zinc was significantly greater from biofortified wheat than from non-biofortified wheat [32]. These findings were corroborated when the absorption of zinc in whole and refined flour from postharvest fortified wheat and agronomically biofortified wheat were tested prior to a randomized controlled efficacy trial in India [33]. Two efficacy trials using wheat biofortified by foliar spraying with zinc fertilizer were recently completed: one with 250 schoolchildren in Bangalore and the other with 3,000 pairs of women and children under two in New Delhi.

Farmers are willing to grow biofortified crops and consumers are willing to eat them

Economists conduct studies to understand farmers' willingness to grow biofortified crops and consumers' willingness to pay to purchase them. The aim of these studies is to inform product development, delivery and marketing strategies that will maximize adoption and consumption of biofortified crops. Farmers' willingness to grow biofortified crops is investigated through farmer field day evaluations, monitoring surveys and adoption studies, as well as impact evaluation studies [34], while sensory evaluations (e.g. of appearance, taste, and texture) and willingness to pay studies are conducted to understand consumer acceptance [35].

Vitamin A orange sweet potato

The randomized controlled effectiveness trial in Mozambique and Uganda (2006–2009) evaluated the impact of two delivery models (one providing more intensive training on nutrition and best agronomics practices than the other) on vitamin A OSP adoption, vitamin A intake, and vitamin A status of beneficiary households. The study found that 61 percent and 68 percent of beneficiary households adopted vitamin A OSP in Uganda and Mozambique, respectively, and no significant differences in the adoption, vitamin A intake, and vitamin A status outcomes resulting from the two delivery models [36]. In 2011, a follow-up study in Uganda found that adoption rates remained high in two of the three study areas and that nutrition information was well retained. The area with the lower adoption rates became a major supplier, but not consumer, of vitamin A OSP [37]. These impact evaluations provided a crucial evidence-base for donors and helped inform the scaling up of biofortification in Uganda [38].

Sensory evaluation studies conducted in Uganda, Tanzania, Mozambique, and South Africa showed that consumers liked the sensory attributes of vitamin A OSP, as well as those of various products made with vitamin A OSP such as bread [35]. Studies in rural Uganda revealed that when nutrition information on the benefits of vitamin A OSP was provided, consumers valued the vitamin A-rich orange varieties more than white ones [39]. Another study conducted in Mozambique also found that consumers valued vitamin A OSP and that the value was influenced by information on nutritional benefits [40]. Collectively, these studies highlight the importance of information campaigns in driving demand for vitamin A OSP.

Vitamin A cassava

A consumer acceptance study conducted in two states of Nigeria tested vitamin A cassava *gari* against local *gari*. In the state of Oyo, the local *gari* tested was made with white cassava, and in the state of Imo it was yellow (white cassava mixed with red palm oil), in accordance with regional preferences. In Oyo, consumers preferred *gari* made with light yellow cassava even in the absence of nutrition information. Once consumers received information about the nutritional benefits of vitamin A cassava varieties, light-colored yellow cassava remained the most popular, but *gari* made with deeper-colored yellow cassava was preferred over the local variety. In Imo, on the other hand, in the absence of nutrition information, local *gari* was preferred to the *gari* made with either light- or deeper-colored yellow cassava varieties. However, once consumers were told about the nutritional benefits of vitamin A cassava, *gari* made with the deeper-colored yellow cassava was preferred, highlighting the importance of information campaigns in this area [41].

Another study on vitamin A cassava, this time in Kenya, found that both the caregivers (18- to 45-year-olds) and children (7- to 12-year-olds) preferred yellow cassava over white cassava because of its soft texture, sweet taste, and attractive color [42].

Vitamin A maize

In Zambia, farmer field day surveys conducted in 2012 and a monitoring survey conducted in 2015 confirmed a strong preference by farmers for both the production and consumption attributes of vitamin A maize varieties compared with conventional white maize varieties. Farmers appreciated the yield, cob size, and cob-filling characteristics of the new varieties, as well as the taste and aroma of vitamin A maize preparations. Nearly all farmers (97 percent) said they would grow vitamin A maize in the next season and that they were planning to plant four times more seed than they did in the previous (2014–2015) season [43].

A consumer acceptance study conducted in rural Zambia showed that consumers valued *nshima* made with vitamin A maize more than *nshima* from white and yellow maize varieties, even in the absence of nutrition information [44]. When nutrition information was delivered by radio or community leaders, it translated into even greater acceptance of vitamin A maize. The increases in acceptance were similar regardless of the media source, implying that radio—which is significantly less costly than face-to-face messaging—can be used to effectively convey nutrition information. Another study, conducted in rural Ghana, found that consumers valued *kenkey* made with vitamin A maize less than *kenkey* made with either white or yellow maize, but the provision of nutrition information reversed this preference. An information campaign will be key to driving consumer acceptance of vitamin A maize in Ghana [45].

Iron beans

A study conducted in Rwanda in 2015 assessed the adoption and diffusion rates of iron bean varieties after eight seasons of intensive delivery efforts by HarvestPlus and its partners. Data from this nationally representative study

revealed that 28 percent of rural bean-producing households—about half a million households—had planted at least one iron bean variety in at least one of the past eight seasons. In the study season, i.e., the first bean-growing season of 2015, an estimated 20 percent of all bean growers in Rwanda (more than 300,000 rural households) were found to grow iron beans. Further analysis revealed several encouraging findings: awareness of iron beans is high among bean growers in Rwanda, with over two-thirds having heard of iron varieties; diffusion levels are high, with four out of ten farmers receiving planting material from a farmer in their social network; and, the proportion of land farmers allocate to iron beans increases over time (from 48 percent in season one to 70 percent in season six). Additionally, in the study season iron bean varieties made up almost 12 percent of the national bean production, and within households, 80 percent of iron beans produced were used for household consumption [46].

Consumer acceptance studies conducted in rural Rwanda showed that even in the absence of nutrition information, consumers in the Northern Province liked the sensory attributes of a biofortified red iron bean variety more than a white iron bean or local bean variety [47]. Nutrition information had a positive effect on the premium consumers in urban wholesale, and retail markets were willing to pay for iron beans: when provided, both iron bean varieties were preferred to the local variety. When compared across regions, consumers in the rural Western Province and urban wholesale market also had similar preferences for one of the iron bean varieties tested, suggesting potential for linking demand and supply [48]. Another analysis of multiple sensory attributes revealed several opportunities for marketing of iron beans in both rural and urban markets [49]. Similar studies conducted in the Latin America and Caribbean region, e.g., in Colombia [50] and Guatemala [51], also revealed positive results for consumer acceptance of iron beans.

Iron pearl millet

A consumer acceptance study of *bhakri* made with iron pearl millet conducted in rural Maharashtra, India, revealed that even in the absence of information about the nutritional benefits, consumers liked the sensory attributes of iron pearl millet grain and the *bhakri* made from it as much as, if not more than, conventional pearl millet grain and *bhakri*. When nutrition information was provided, consumer acceptance and willingness to pay was even greater [52].

Biofortification is cost-effective

The Copenhagen Consensus ranked interventions that reduce micronutrient deficiencies, including biofortification, among the highest value-for-money investments for economic development. For every dollar invested in biofortification, as much as 17 USD of benefits may be gained [53].

Ex post (after intervention) cost-effectiveness data on vitamin A OSP from the abovementioned randomized controlled effectiveness trial conducted in Uganda demonstrated that biofortification costs 15-20 USD per Disability Adjusted Life Year (DALY) saved [36]. For other target countries where large-scale delivery efforts have recently started or are about to begin, ex-ante (before intervention) analyses were conducted as well to calculate the expected cost per DALY saved for each context [54, 55]. Results of all these studies and a more recent review of ex-ante analyses [56] pointed out that biofortification is highly cost-effective according to the World Bank criteria [57]. In addition, cost-effectiveness of biofortification is significantly higher in most countries analyzed, when compared to other interventions, such as supplementation and fortification [54, 55]. Exceptions typically involved scenarios with low substitution and/or consumption of the staple crop. Across studies which use health statistics and average country-level data to determine the potential cost-effectiveness of biofortification under

different scenarios, showed that even in countries where relatively few DALYs are lost due to micronutrient deficiency, biofortification is expected to have an advantageous benefit-cost ratio [56].

Overall food systems provide the most sustainable means to add essential vitamins and minerals into the diet. As the evidence summarized above can attest, biofortification is scientifically proven to be a feasible, efficacious, cost-effective sustainable and scalable agricultural-nutrition intervention. Biofortification can deliver essential micronutrients to malnourished rural and vulnerable populations who may have limited access to diverse diets, supplements and/or commercially fortified foods [58]. More than two billion people in the world are micronutrient deficient. Once this revolutionary innovation is scaled, it can significantly reduce the number of people suffering from hidden hunger and ensure that they have healthy and productive lives.

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