Biofortification in Underutilized Staple Crops for Nutrition in Asia and Africa

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ABSTRACT: Malnutrition is one of the biggest public health challenges of the century with about 2 billion people affected by it globally. Biofortification is the process of breeding micronutrients traits into staple food crops, which is bioavailable to make a positive measurable impact to the population that eats such staples on a daily basis. It is a cost-effective, sustainable strategy and complementary in nature to the existing market interventions. Iron pearl millet, iron beans, vitamin A cassava and orange sweet potato can contribute to increase household nutrition in the Asia and Africa. Over the years evidences gathered by partners in crop breeding, nutrition studies and delivery experiences will help to build the foundation for scaling out further to reach millions who need the most.

Key words: Biofortification, Iron beans, Iron pearl millet, Orange sweet potato, Vitamin A cassava

Introduction

Mineral and vitamin deficiencies are a serious public health problem in Asia and Africa. Two billion people in the world suffer from various forms of malnutrition (FAO, 2011). Malnutrition is an underlying cause of death of 2.6 million children each year - a third of child deaths globally (IFAD/FAO/WFP, 2011; Black *et al*., 2008). In general, dietary quality is poor, with high dependence on cereal and root staples for the bulk of dietary energy consumption, particularly among the poor (Food and Agriculture Organization of the United Nations (FAO, 2015). Low incomes and high prices for non-staple foods such as vegetables, fruits, pulses, and animal products are the major constraints to improved dietary quality. Non-staple foods are often dense in vitamin and minerals, and bioavailability is particularly high for animal products, yet animal products are the most expensive source of dietary energy. The poor eat large quantities of food staples to acquire dietary energy. The health consequences of poor dietary quality are well known- high morbidity and infant mortality rates, compromised cognitive development for children, stunting and low economic productivity. Eating habits of the people depends on many factors, including cultural, geographical, environmental, and seasonal factors. One of the key underlying causes leading to poor dietary quality is that current food systems do not provide minerals and vitamins in sufficient quantities at affordable prices for the poor. Poverty is a major factor that limits intake of adequate, nutritious food, which must be available, accessible, and affordable to the poor. Therefore,

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long-term agricultural investments and policies to improve the availability and affordability of more nutritious foods, such as biofortification, must be made an important part of the solution.

Biofortification is the process of breeding nutrients into staple food crops; it is a cost-effective and sustainable agricultural investment that can help to reduce mineral and vitamin deficiencies, especially in the diets of the rural poor. Research in plant breeding and human nutrition, has been largely successful and continues to generate new evidences. One of the critical task is to scale up the supply and demand of biofortified crops and communicate the benefits that are now available to farmers, particularly by impoverished and malnourished rural households, and to embed biofortification as a mainstream approach in the core plant breeding programmes.

Fortification is particularly effective for urban consumers, who purchase foods that have been commercially processed and fortified. It is less suitable for reaching rural consumers who often do not have access to or the incomes to afford commercially produced foods.

Justification for Biofortification

Biofortification provides a comparatively cost-effective, sustainable, and long-term means of delivering vitamins and micronutrients to households that might otherwise not have access to, or that cannot afford to have, a fully balanced diet. No single intervention will solve the problem of micronutrient deficiency, but biofortification complements existing interventions (discussed above) to provide micronutrients to the most vulnerable people in a comparatively inexpensive, cost-effective, and sustainable manner (Bouis, 1999; Nestel *et al*., 2006; Hotz and McClafferty, 2007; Pfeiffer and McClafferty, 2007; Qaim *et al*., 2007; Meenakshi *et al*., 2010).

Biofortification provides a feasible means of reaching malnourished populations who may have limited access to diverse diets, supplements, and commercially fortified foods. The strategy seeks to put the micronutrient-dense trait (such as for zinc, iron or vitamin A) in basic staple food crops that are being grown and consumed by people in developing countries and that have farmers' preferred agronomic traits, such as high yield. In contrast to complementary interventions, such as fortification and supplementation that begin in urban centers, biofortified crops reach consumers in rural areas first, since most rural farming households consume what they grow. As farmers produce and market surplus biofortified staple food crops, the intervention reaches urban areas. There are several advantages of growing biofortified crops:

- Unlike the continual financial outlays required for supplementation and commercial fortification programmes, a one-time investment in plant breeding can yield micronutrient rich planting materials for farmers to grow for years to come.
- Biofortified varieties bred for one country can be evaluated for performance and adaption to other countries, thereby potentially multiplying the benefits of the initial investment. As seed producers incorporate biofortified crops into their product lines, biofortification becomes more sustainable over time, if regulatory mechanisms are in place to maintain standards and related claims.
- While recurrent expenditures are required for monitoring and maintaining these traits in crops, these are low compared to the cost of the initial development of the nutritionally improved crops. Once established, the cost of maintaining biofortified traits represents a small portion of ongoing global investment in crop improvement.

Status on the Crop Development of Biofortified Staple Food Crops under HarvestPlus Programmes

There are two common approaches to biofortification, agronomic and conventional breeding. Early in the conceptual development of the HarvestPlus project, a working group of nutritionists and plant breeders established nutritional breeding targets. Based on food consumption patterns of target populations, HarvestPlus estimated nutrient losses during storage and processing, and nutrient bioavailability (Hotz and McClafferty, 2007). Breeding targets for biofortified crops designed to meet the specific dietary needs and consumption patterns of women and children. Targets were set such that for preschool children (4-6 years old) and for non-pregnant, non-lactating women of reproductive age.

Iron-biofortified beans and iron biofortified pearl millet would provide approximately 60 per cent of the Estimated Average Requirement (EAR) for iron. Provitamin A biofortified cassava and sweet potato would provide at least 50% of provitamin A.

Originally, established using limited data on consumption patterns, as well as nutrient stability and retention in the biofortified crops (Bouis *et al.*, 2011), the breeding targets were refined to meet the target EARs as more data became available (Tables 1and 2).

Table 1. Information and assumptions used to set revised target levels for micronutrient contents of biofortified primary staple food crops

		Rice (Polished)	Wheat (Whole)	Pearl Millet (Whole)	Beans (Whole)	Maize (Whole)	Cassava (Fresh-weight)	Sweet Potato (Fresh-weight)
Per Capita Consumption	Adult Women (g/day)	420	260	220	200	290	940	400
	Children 4-6 yr (g/day)	160	70	85	100	170	350	200
Iron	Additional % of EAR to achieve				>30			
	Total % of EAR to achieve				>70			
	EAR, non pregnant, non lactating women (µg/day)				1460			
	EAR, children 4-6 yr (µg/day)				500			
	Micronutrient retention after processing (%)			90	90			
	Bioavailability (%)			7.5	7			
	Baseline micronutrient content (µg/g)			47	50			
	Additional content required (µg/g			+30	+44			
	Final target content (µg/g)			77	94			
Zinc	Additional % of EAR to achieve				>25			
	Total % of EAR to achieve				>60			
	EAR, non pregnant, non lactating women (µg/day)				2960			
	EAR, children 4-6 yr (µg/day)				1390			
	Micronutrient retention after processing (%)	90	95			90		
	Bioavailability (%)	25	15			20		
	Baseline micronutrient content (µg/g)	16	25			25		
	Additional content required (µg/g	+12	+12			+12		
	Final target content (µg/g)	28	37			37		
Provitamin A	Additional % of EAR to achieve				>50			
	Total % of EAR to Achieve				>50			
	EAR, non pregnant, non lactating women (µg/day)				500			
	EAR, children 4-6 yr (µg/day)				275			

		Rice (Polished)	Wheat (Whole)	Pearl Millet (Whole)	Beans (Whole)	Maize (Whole)	Cassava (Fresh-weight)	Sweet Potato (Fresh-weight)
	Micronutrient retention after processing (%)					37	35	35
	Bioavailability ratio (µg to RAE)					6:1	5:1	12:1
	Baseline micronutrient content (µg/g)					0	0	0
	Additional content required (µg/g					+15	+15	+70
	Final target content (µg/g)					15	15	70
EAR-estimated average requirement; RAE- retinol activity equivalent								

Table 2. Information and assumptions used to calculate the contribution of biofortified secondary staple food crops to estimated average requirements (EAR) for iron, zinc and provitamin A

	Consumption Levels (g/day)	Lentil (decorticated grain*)		Cowpea (whole, DW)	Sorghum (decorticated grain*)		Irish Potato (FW)**		Banana and Plantain (FW)
Micronutrient(s)		**Iron**	**Zinc**	**Iron**	**Iron**	**Zinc**	**Iron**	**Zinc**	**VitA**
EAR, non pregnant, non lactating women (µg/day		1460	2960	1460	1460	2960	1460	2960	500
EAR, children 4-6 yr (µg/day)		500	1390	500	500	1390	500	1390	275
Micronutrient retention after processing (%)		85	90	90	50	60	80	85	50
Bioavailability (%)		5	25	2.5	2	8	6	25	8
Baseline micronutrient content (µg/g)		65	46	54	30	22	4.8	4.2	10
Current additional content achieved (µg/g)		60	28	40	15	16	1.5	2.4	60
Current final content achieved (µg/g)		125	74	94	45	38	6.3	6.6	70
Max. genetic variation discovered (µg/g)		110	78	95	70	50	9.0	9.6	>100
Children 4-6 yr:	20	21	24	8					
Total % of EAR achieved, based on per capita	100				9	13	6	10	102
Consumption (g/day)	200				18	26	12	20	204
	40	15	23	6					
Adult Women:	50	18	28	7					
Total % of EAR achieved, based on per capita	300				9	18	6	14	168
Consumption (g/day)	400				12	25	8	19	224
EAR, estimated average requirement									
*assuming<16% moisture; **assuming 30% dry weight basis									

Major steps involved in the biofortification process are:

- The HarvestPlus approach to breeding first assesses whether sufficient genetic variation exists in elite or germplasm bank materials for a particular trait of interest.

- Plant breeders screen existing crop varieties and accessions in global germplasm banks, including both adapted and non-adapted material such as landraces and wild relatives.
- Initial research indicated that selection of lines with diverse vitamin and mineral profiles could be exploited for genetic improvement (Beebe *et al*., 2000; Monasterio and Graham. 2002; Pfeiffer and McClafferty, 2007; Jiang *et al*., 2008; Menkir, 2008; Menkir *et al*., 2008; Gomez-Becerra *et al*., 2010a; Talukder *et al*., 2010; Velu *et al*., 2011; Ashok Kumar *et al*., 2012; Dwivedi *et al*., 2012; Fageria *et al.,* 2012).
- When lines with these traits are identified, they are used in early-stage product development and parent building. Intermediate stage product development takes place at CGIAR centers, where breeding materials with improved nutrient content and high agronomic performance, as well as preferred consumer qualities are developed.
- Final product development takes place at both CGIAR centers and National Agricultural Research Systems (NARS). National research partners may carry out further crosses with locally adapted materials to develop final products that meet specific traits required by local producers and consumers.
- After promising high yielding, high-nutrient lines emerge, they are tested across a wide range of environments side-by-side with locally preferred varieties. Participatory variety selection (PVS) involves farmers and/or consumers who compare crop and food preparation performance to select the preferred materials. The best-performing lines are then submitted to national performance trials conducted by governmental institutions prior to release.
- The breeding process takes six to ten years to complete. As of 2017, HarvestPlus partners have released more than 158 biofortified varieties of 10 crops in 26 countries.

HarvestPlus along with the partners has used two strategies to shorten the time to market for biofortified crops: (i) Identifying adapted varieties with significant micronutrient content for release and/or dissemination as "fast-track" varieties; and (ii) while varieties with target micronutrient content are still under development, deploying multi-location regional trials across a wide range of countries and sites to accelerate release processes by increasing available performance data of elite breeding materials. Regional trials also include already released biofortified varieties and generate data on their regional performance. By substituting temporal-by-spatial environmental variation in large-scale regional genotype-by-environment (GxE) testing, testing steps can be eliminated and also time to market shortened by one to two years.

Status of Crop Development Progress to Date

Provitamin A Orange Sweet Potato is widely consumed in sub-Saharan Africa. Conventionally bred orange sweet potato (OSP) containing provitamin A was the first biofortified crop developed and released by the International Potato Center (CIP), the HarvestPlus, and its partners. Plant breeders have produced several OSP varieties with provitamin A content of 30-100 ppm, exceeding the target level of 32 ppm. The National Crops Resources Research Institute (NaCRRI), with the support of CIP, conducts breeding research in Uganda. As the provitamin A trait is mainstreamed in breeding populations, ongoing OSP breeding focuses on tolerance to biotic and abiotic stress while maintaining/enhancing provitamin A levels. In Uganda, a HarvestPlus focus country, HarvestPlus coordinates with NaCRRI and CIP to ensure a continuous flow of improved varieties. Two orange-fleshed landrace cultivars named 'Ejumula' and 'SPK004' ('Kakamega'), with the full provitamin A target, were released in 2004, and two additional varieties named 'Vita' (NASPOT 9 O) and 'Kabode' (NASPOT 10 O) were released in 2007. In 2013, two new OSP cultivars (NASPOT 12 O and NASPOT 13 O) with wide adaptation, high root yield, and high dry matter content were released. Biofortified OSP varieties have been released in more than 15 countries across sub-Saharan Africa, and are being introduced in many parts of Asia (China, Bangladesh, and India) and Latin America. At the 2016 Annual Sweet Potato Speed Breeders Meeting in Kenya, more than 30 sweet potato breeders working in 14 African countries signed a commitment to mainstreaming beta-carotene into national breeding efforts, striving to ensure that at least 50 per cent of the clones submitted for release are biofortified, orange-fleshed types.

Provitamin A yellow cassava is a dietary staple in much of tropical Africa, and grows well in poor soils with limited labour requirements. Screening of cassava accessions from the International Center for Tropical Agriculture (CIAT) germplasm collection found a range of 0-19 ppm of provitamin A in existing cassava varieties, exceeding the breeding target of 15 ppm (Chavez *et al*., 2005; Ceballos *et al*., 2012). Studies on GxE interaction for carotenoid content did not find significant changes in the relative ranking of genotypes, and found high (>0.6) heritability of carotenoid content in cassava roots (Ssemakula and Dixon, 2007; Ssemakula *et al*., 2007; Morillo *et al.*, 2012; Njoku *et al*., 2015). Rapid-cycling recurrent selection was used to shorten the normal breeding cycle from eight years to two to three years for high carotenoid content (Ceballos *et al.,* 2013). Breeding programmes for provitamin A cassava are based at CIAT and the International Institute of Tropical Agriculture (IITA). CIAT generates high-provitamin A sources via rapid cycling in pre-breeding and provides *in vitro* clones and seed populations to IITA and the national research programmes in two target countries, Nigeria and the Democratic Republic of Congo (DRC), for local adaptive breeding. These national research programmes are the Nigerian National Root Crops Research Institute (NRCRI) and the Institute National pour l'Etude et la Recherche Agronomiques (INERA) in the DRC. Cassava varieties that best meet farmer-preferred traits include high yield, early maturity, tolerance to pests and diseases, dry matter content, poundability, mealiness, sweetness, ease of peeling, marketability, and in-ground storage durability (Njoku *et al*., 2015). Genotype-by-environment (GxE) testing is used to verify that varieties proposed for release are widely adapted and stable across different environments (Maroya *et al*., 2012). Investments in marker-assisted selection have identified phytoene synthase 2 (PSY2) as one of the major alleles for provitamin A accumulation in cassava roots, and markers are beginning to be tested as a breeding tool, in addition to the ongoing phenotypic selection (Welsch *et al*., 2010; Ferguson *et al*., 2011; Rabbi *et al*., 2014).

Iron bean (common bean) is the most common food legume in Latin America and eastern and southern Africa. Bush beans are cultivated in low to mid-altitudes and climbing beans in mid- to high-altitude areas. Initial screening found ranges of 30-110 ppm iron (and 25-60 ppm zinc) in cultivated and wild beans from the germplasm collection at CIAT, exceeding the target level of 94 ppm for iron. The highest levels were found in wild and weedy germplasm (Guzman-Maldonado *et al*., 2000). High-iron genotypes were used to initiate crosses to combine the high-mineral trait with acceptable grain types and agronomic characteristics. Grain mineral content is influenced by environmental factors such as soil organic matter and precipitation (Beebe, 2012; Rai *et al*., 2014a). Genotype-by-environment (GxE) testing is, therefore, used to identify materials with stable mineral accumulation across sites and generations (Blair *et al*., 2010). Biofortified lines are developed by the breeding programme at CIAT and are being evaluated for local adaptation by national programmes in several East and Southern African countries as well as in South and Central America. The lines are at varying stages in the breeding pipelines in each of these countries. Breeding programmes in African target countries Rwanda (Rwanda Agriculture Board-RAB) and the DRC (L'Institut National pour l'Etude et la Recherche Agronomique-INERA) have developed crosses locally and are assuming a greater portion of the selection work. A full breeding pipeline consists of both locally developed germplasm and CIAT introductions.

In Rwanda, four first-wave, fast-track varieties (two bush, two climber) were released in 2010 and five second-wave climbing bean varieties in 2012. In the DRC, five first-waves, fast-track varieties (three bush, two climber) were identified for release and dissemination in 2011 and five second-wave varieties (three bush, two climber) in 2013. Five varieties (two climbers, three bush) were released in Uganda in 2016. Released bean varieties contain about 60 per cent of the iron target level (+44 ppm more iron) in the first wave, 80 per cent in the second wave, and 100 per cent in the third wave. In addition, they are resistant to major pests and diseases have good yield and farmer preferred end-use quality, and different grain colors and sizes that cover a range of major market classes. New climber and bush bean lines with 90-100 per cent target increment for iron are in advanced line validation trials to identify agronomically competitive third-wave varieties. Current breeding efforts focus on developing climate-smart iron beans that are high iron, higher yielding, and tolerant to drought and heat. Additional crop improvement research is underway to combine a low physic acid (LPA) mutation with the iron trait, which increases the bioavailability of iron when beans are consumed.

Iron Pearl Millet (pearl millet) breeding programme is based at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in India. Initial screening of germplasm accessions found ranges of 30-76 ppm iron (and 25-65 ppm zinc) in pearl millet, nearly reaching the full breeding target of 77 ppm (that is, an increment of +30 ppm additional grain iron compared to 47 ppm on average in non-biofortified germplasm). High-iron genotypes were selected to initiate crosses (Velu *et al*., 2007; Gupta *et al*., 2009). High correlation between iron and zinc content indicated good prospects for simultaneous selection for the two micronutrients (Velu *et al*., 2008 a; b; Rai *et al*., 2013). Both micronutrients are largely under additive genetic control, implying that iron hybrids will require both parental lines to have high iron density (Govindaraj and Rai, 2016; Govindaraj *et al*., 2016; Velu *et al*., 2011). Genotype-by-environment (GxE) testing was used to evaluate the most promising local germplasm and potential parents and verify that mineral accumulation was stable across sites and generations (Rai *et al*., 2012).

The breeding pipeline at ICRISAT initially included open-pollinated variety (OPV) development. However, since approximately 70 per cent of the pearl millet area in India is planted to hybrids, emphasis is now placed on hybrids and hybrid-parent development. The major focus of the breeding programme is to develop higher yielding, high-iron hybrids with stable yield and iron performance for the major pearl millet growing areas in India. Major traits include drought tolerance, resistance to downy mildew, and end-use quality traits. Pearl millet biofortification research at ICRISAT is carried out in alliance with HarvestPlus, the ICAR-All India Coordinated Pearl Millet Improvement Project, six State Agricultural Universities, more than 15 seed companies, and two state seed corporations. To ensure long-term sustainability, HarvestPlus engages seed companies in GxE testing of hybrids and inbred lines developed at ICRISAT, and encourage them to develop their own high iron hybrids for commercialization.

In 2014, Dhanashakti, an OPV was developed by ICRISAT in collaboration with Mahatma Phule Krishi Vidyapeeth, Rahuri under ICAR- All India Coordinated Research Project on Pearl millet. The first wave of high-iron and high-yielding hybrid, ICMH-1201, was developed by ICRISAT under HarvestPlus Biofortification Programme, widely tested over 48 field trials during three consecutive years. This hybrid contains +28 ppm additional iron (more than 90% of the target increment) and has 38 per cent higher grain yield than ICTP 8203. Second wave of biofortified iron hybrids HHB 229 (contains 73.0 ppm and zinc 41.0 ppm), AHB1200 (contains 73.0 ppm and zinc 40.00 ppm) developed by ICRISAT in partnership with CCS-Haryana Agricultural University, Hisar and Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani respectively in collaboration with under the ICAR-All India Coordinated Research Project on Pearl Millet.

The success of pearl millet biofortification in India suggests that similar achievements could be realized for Western and Central Africa (WCA). The WCA region has the largest area under millets in Africa, of which more than 90 per cent is pearl millet. Studies of pearl millet landraces and other locally adapted materials from Niger and Sudan showed promising ranges of mineral density (Bashir *et al*., 2014 a, b; Pucher *et al*., 2014). The most promising iron pearl millet OPVs are currently being tested on-farm at more than 30 locations across five countries in WCA. Two OPV varieties (GB8735 and ICTP8203) have been selected as candidates for fast tracking in Niger, Ghana and Senegal.

Delivery Strategies and Results to Date

Vitamin A Cassava in Nigeria

Delivery may be conceptualized and discussed as three broad sets of activities, which to some extent are interdependent and must be implemented simultaneously: (i) cassava stem multiplication and extension to farmers, (ii) creating and building consumer demand, and (iii) connecting supply and demand through markets. The foundation of the successful introduction of yellow cassava in the Nigerian food system and its ultimate sustainability is consumer demand. However, a certain investment and momentum in the supply chain must be established initially before investing heavily in building consumer demand. Scaling up the supply of cassava tubers stem multiplication HarvestPlus employs two major channels (public and commercial) in the multiplication of vitamin A cassava in Nigeria. Generally, public multiplication programmes funded by the government, development agencies, farmer and community-based associations have social responsibilities aimed at alleviating poverty and food security gaps. Commercial multiplication programmes, funded by private investors, aim at making profit. The former channel ensures horizontal access, where every farmer can access a small quantity of stems for planting. While the latter is vertical and demand-driven, it ensures sufficient seed-stem supply for larger-scale production. Starting with the distribution of small free stem packs allows farmers to test the new biofortified varieties with minimal risk, and they can later link to commercial seed farms to purchase stems in larger quantities.

In 2011, the biofortification crop delivery programme started with stem multiplication in ten local government areas (LGA) in each of the following four states; Oyo in the West, Imo in the East, Akwa Ibom in the South and Benue in the North. In 2012, the programme expanded to six villages in each LGA making a total of 60 villages per state and 240 villages in the four targeted states. The programme rolled out to 18 more states between 2013 and 2015, thus covering over 60 per cent of all the states in the country and over 80 per cent of the major cassava producing states even though the level of coverage differs from one state to the other.

Marketing activities along the value chain are necessary to ensure that effective demand can pull the supplies of yellow cassava from rural production to rural and urban markets. Available data from vitamin A cassava investors suggest that '*gari*' is the most traded vitamin A cassava product, accounting for 58 per cent of total sales in 2015. '*Fufu*' accounted for 30 per cent of the total sales, followed by flour (12%), resulting from the high demand for vitamin A cassava-based snacks and confectioneries like queen cake, combo-bits, and combo-strips.

Creating demand consumer marketing using print, television, and radio media were used extensively to communicate the importance of vitamin A cassava to consumers to create demand, and to investors to increase product supply. Radio and television reach jingles were developed and translated into five local languages for creating awareness on radio and television prior to stem distribution. Nutritious Food Fair (NFF) creates awareness and builds linkages among farmers, processors, marketers and consumers. In 2016, four million people were growing and consuming vitamin A cassava.

Iron Beans in Rwanda

In Rwanda, the crop delivery work began in 2011, following the first biofortified bean varietal releases in 2010. According to monitoring data, HarvestPlus and its partners had delivered close to 3,000 metric tons of iron bean seed to over 800,000 farming households by the end of 2015. Delivery may be conceptualized and discussed as three broad sets of interdependent activities: (i) bean seed multiplication and delivery to farmers; (ii) creating and building consumer demand; and (iii) connecting supply and demand through markets. The foundation for successful introduction of iron beans in the Rwanda food system and, ultimately for its sustainability, is consumer demand. However, investment in strengthening the supply chain must be established prior to heavy investment in generating consumer demand. This section presents the delivery activities in Rwanda, followed by additional experiences from DRC.

To facilitate the production of iron bean seed, HarvestPlus worked closely with RAB, contracting individual commercial farmers, farmer-based cooperatives, and small seed companies to multiply biofortified varieties. To increase available seed for the 2015 planting season and beyond, HarvestPlus collaborated with established local and regional seed companies for seed multiplication, with RAB certifying the biofortified seed. These partners include SeedCo, Kenya Seed Company, Rwanda Improved Seed Company (RISCO), and WinWin Agritec. In Rwanda, the biofortification crop delivery programme started in 2011 in four districts, Nyagatare, Kirehe, Ngoma and Musanze. In 2012, the programme rolled out to 13 additional districts and now operates throughout the country. Delivery of iron beans in Rwanda initially occurred through various platforms and mechanisms, including agro-dealers, farmer-based cooperatives, direct marketing in local markets, and a payback system. In direct marketing, marketing agents sold iron bean seed at local markets, reaching a large number of farmers with relatively small quantities of seed. This allowed farmers to try the varieties before committing to greater production.

Agro-dealers sold iron bean seeds directly to farmers and had the advantage of being close to farmers throughout the year.

As biofortified beans gained traction in the market, seed companies and agro-dealers became increasingly interested in iron beans in their product lines. From 2015 on, HarvestPlus has been working closely with the private sector to scale up production and delivery of iron bean seeds.

There is a secondary effort to brand biofortified beans through the value chain, which requires educating farmers and consumers about the specific characteristics- including shape, color, and size – that allow for the identification of biofortified varieties. Radio talk shows increase awareness among farmers and general consumers about iron bean production, seed availability, and nutritional benefits. A media-based awareness campaign uses entertainment to reach the public and consumers of iron beans with nutritional messages. This campaign has been conducted in partnership with locally renowned musicians and journalists and included a music video and outreach tour touting the benefits of growing and consuming iron beans in Rwanda. In 2016, two million people were growing and consuming iron beans.

Orange Sweet Potato in Uganda

Research conducted in Mozambique and Uganda that provided solid evidence (collected from 2002-2009) that an integrated agriculture-nutrition-marketing intervention using Orange sweet potato (OSP) as a key entry point could significantly and positively impact on young child vitamin A intakes. The three pillars of the integration are: (i) agriculture-with OSP providing a low cost, easy to grow bioavailable source of vitamin A; (ii) nutrition-both producers and consumers need to be informed of the nutritional value of OSP (demand creation campaigns) and change agents need to work with caregivers to ensure they have core, basic knowledge of good dietary and feeding practices and how to incorporate OSP effectively into the young child diet as well as their own; and (iii) marketing-opportunities to commercialize OSP surplus stimulates OSP uptake and rates of permanent adoption. Managing the "seed system" based on vines that are easily shared among growers and hence, typically of limited interest to private sector seed companies, is critical to success. The five cases described below vary depending on whether the major outcomes are nutrition improvement (four of the cases) or cash generation (the Rwanda case study).

Integrated agriculture-nutrition-marketing: case study of Uganda (2011 to date). In Uganda, the going-to-scale dissemination strategy led by HarvestPlus has a three pronged approach integrating agriculture, nutrition and marketing. Principal target groups are children under five years of age and women of child-bearing age. This approach has involved establishing a self-sustaining seed system with trained vine multipliers, ensuring availability of vines to both smallholder farmers and other partners. Local laboratories propagate disease-free or "clean" pre-basic cuttings (planting material) and train multipliers receiving the cuttings on agronomy, post-harvest handling, pest and disease control, and vine conservation.

Promotional activities, including community dramas, field days, and radio campaigns, have been conducted to increase the level of awareness of nutritional benefits of the crops, and thus increase demand and uptake by both government and non-governmental organizations (NGOs). An increasing number of NGOs (for example, World Vision, Save the Children, and Finnish Refugee Council) are purchasing the cuttings. In addition, farmers with surplus production are trained in post-harvest handling and value addition and linked to traders and markets. Commercial farmers are engaged to increase production of OSP and the volumes marketed. HarvestPlus also supports offseason production where possible to enable a reliable and robust supply to markets and institutions (such as schools and prisons). In 2016, a total of 550,000 people were consuming OSP in Uganda

Iron Pearl Millet in India

An iron version of one of the most popular OPVs, ICTP 8203, was developed by ICRISAT, commercialized in 2012 with in partnership with Nirmal Seeds for Maharashtra, India. Due to its high iron content (exceeding

80% of the iron target increment) and wide adaptation, ICTP 8203-Fe was released and notified under the name "Dhanashakti" in 2014 for cultivation in all pearl millet-growing states of India (Rai *et al*., 2014a; b). Dhanashakti was also included in the Nutri-Farm Pilot Project, initiated by the Government of India, for addressing iron deficiency (Purushottam Singh and Uddeen, 2016). Nirmal Seeds Company initiated commercial production of Dhanashakti in 2012 and at the end of 2017, the variety has been marketed to more than 90,000 farmers, mostly in Maharashtra. From 2016 two public sector companies, Mahabeej and KSSC initiated sales and distribution of Dhanashakti in Maharashtra and Karnataka, respectively. The first high-iron and high-yielding hybrid, ICMH-1201, was developed by ICRISAT. Shakti Vardhak Seeds commercialized under its brand name Shakti-1201 since 2014 (Purushottam Singh and Uddeen 2016). Promotional activities were engaged with HarvestPlus partners like product demonstrations, mobile campaign, marketing collaterals with nutrition messaging, farmers meetings. In collaboration with external marketing agency, market research study was conducted to understand the consumer insights towards biofortified crops. At the end of 2017, 465,000 people were consuming iron pearl millet in India.

Conclusions

Agricultural investments and policies in Biofortification will not only improve the availability and affordability of more nutritious food, but also will help in placing the solution in the hands of farmers and the communities (Bouis, 2000). In the long-term, increasing the production of micronutrient-rich foods and improving dietary diversity will substantially reduce micronutrient deficiencies (Bouis *et al*., 2011). Biofortification provides a feasible means of reaching malnourished populations in relatively remote rural areas, delivering biofortified foods to people with limited access to commercially marketed fortified foods, which are more readily available in urban areas. Biofortification and commercial fortification, therefore, are highly complementary. The biofortification strategy seeks to take advantage of the consistent daily consumption of large amounts of food staples by households, including women and children, who are most vulnerable for micronutrient malnutrition. Biofortification in pearl millet can help in securing household nutrition security of the population, especially millions in the arid and semi-arid regions of the country that consume pearl millet in their daily diet. Favorable policies for linking it to the existing public food and nutrition programmes, price incentive for primary grain producers can help to trigger demand. Public private partnership (PPP) of value chain players will help to build foundation for scaling out biofortified crops to create long-term sustainable market. Biofortification is a cost-effective agriculture-based strategy for a sustainable solution for public health and nutrition.

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