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Biofortification: Progress toward a more nourishing future

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ABSTRACT

Biofortification, the process of breeding nutrients into food crops, provides a sustainable, long-term strategy for delivering micronutrients to rural populations in developing countries. Crops are being bred for higher levels of micronutrients using both conventional and transgenic breeding methods; several conventional varieties have been released, while additional conventional and transgenic varieties are in the breeding pipeline. The results of efficacy and effectiveness studies, as well as recent successes in delivery, provide evidence that biofortification is a promising strategy for combating hidden hunger. This review highlights progress to date and identifies challenges faced in delivering biofortified crops.

1. Justification

In the past 40 years, agricultural research for developing countries has focused on increased cereal production. Recently, there has been a shift: agriculture must now not only produce more calories to reduce hunger but also more nutrient-rich food to reduce hidden hunger.[1] One in three people in the world suffer from hidden hunger, caused by a lack of minerals and vitamins in their diets, which leads to negative health consequences (Kennedy et al., 2003).

Biofortification, the process of breeding nutrients into food crops, provides a comparatively cost-effective, sustainable, and long-term means of delivering more micronutrients. Biofortified staple foods cannot deliver as high a level of minerals and vitamins per day as supplements or industrially fortified foods, but they can help by increasing the daily adequacy of micronutrient intakes among individuals throughout the lifecycle (Bouis et al., 2011). Note that biofortification is not expected to treat micronutrient deficiencies or eliminate them in all population groups. No single intervention will solve the problem of micronutrient malnutrition, but biofortification complements existing interventions to sustainably provide micronutrients to the most vulnerable people in a comparatively inexpensive and cost-effective way (Bouis, 1999; Nestel et al., 2006; Pfeiffer and McClafferty, 2007; Qaim et al., 2007; Meenakshi et al., 2010).

Biofortification provides a feasible means of reaching malnourished rural populations who may have limited access to diverse diets, supplements, and commercially fortified foods. The biofortification strategy seeks to put the micronutrient-dense trait in those varieties that already have preferred agronomic and consumption traits, such as high yield. Marketed surpluses of these crops may make their way into retail outlets, reaching consumers in first rural and then urban areas, in contrast to complementary interventions, such as fortification and supplementation, that begin in urban centers.

Unlike the continual financial outlays required for supplementation and commercial fortification programs, a one-time investment in plant breeding can yield micronutrient-rich planting materials for farmers to grow for years to come. Varieties bred for one country can be evaluated for performance in, and adapted to, other geographies, multiplying the benefits of the initial investment. 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 and the establishment, institutionally speaking, of nutrient content as a legitimate breeding objective for the crop development pipelines of national and international research centers.

Currently, agronomic, conventional, and transgenic biofortification are three common approaches. Agronomic biofortification can provide temporary micronutrient increases through fertilizers. Foliar application of zinc fertilizer, for example, can increase grain zinc concentration by up to 20 ppm in wheat grain in India and

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[1] An important part of the overall solution is to improve the productivity of a long list of non-staple food crops. Because of the large number of foods involved, achieving this goal requires a very large investment, the dimensions of which are not addressed here.

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Pakistan, but only in the season it is applied (Zou et al., 2012). This is nearly the full target increment set by nutritionists and sought in plant breeding (further described below). About half the target increment can be realized in rice; in maize, foliar application resulted in only a small effect (Phattarakul et al., 2012; Kalayci et al., 2011). This approach could complement plant breeding efforts but further research is needed.

Biofortification can be achieved through conventional plant breeding, where parent lines with high vitamin or mineral levels are crossed over several generations to produce plants that have the desired nutrient and agronomic traits. Transgenic approaches are advantageous when the nutrient does not naturally exist in a crop (for example, provitamin A in rice), or when sufficient amounts of bioavailable micronutrients cannot be effectively bred into the crop. However, once a transgenic line is obtained, several years of conventional breeding are needed to assure that the transgenes are stably inherited and to incorporate the transgenic line into varieties that farmers prefer. While transgenic breeding can sometimes offer micronutrient gains beyond those available to conventional breeders, many countries lack legal frameworks to allow release and commercialization of these varieties.

1.1. *Implementing biofortification*

For biofortification to be successful, three broad questions must be addressed:

Can breeding increase the micronutrient density in food staples to target levels that will make a measurable and significant impact on nutritional status?

When consumed under controlled conditions, will the extra nutrients bred into the food staples be absorbed and utilized at sufficient levels to improve micronutrient status?

Will farmers grow the biofortified varieties and will consumers buy/eat them in sufficient quantities?

To answer these questions, researchers must carry out a series of activities classified in three phases of discovery, development, and dissemination. This impact pathway is illustrated in Fig. 1 and discussed in greater detail in Bouis et al. (2011).

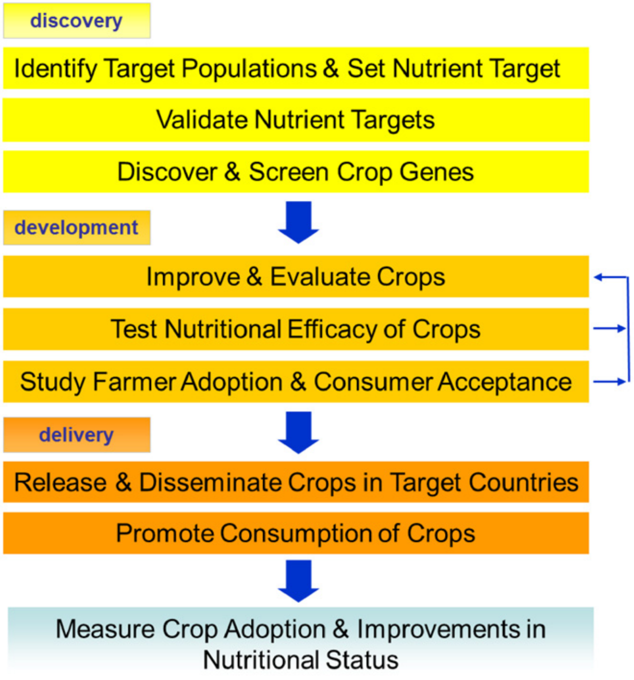

Fig. 1. Impact pathway.

1.1.1. *Discovery*

The overlap of cropping patterns, consumption trends, and prevalence of micronutrient malnutrition, as well as *ex ante* cost–benefit analyses, determine target populations and focus crops. Nutritionists then work with breeders to establish nutritional breeding targets. These target levels take into account the average food intake and habitual food consumption patterns of target population groups, nutrient losses during storage and processing, and nutrient bioavailability (Hotz and McClafferty, 2007).

Under HarvestPlus, breeding targets are set such that, for pre-school children 4–6 years old and for non-pregnant, non-lactating women of reproductive age, the incremental amount of iron will provide approximately 30% of the Estimated Average Requirement (EAR), that incremental zinc will provide 40% of the EAR, and that incremental provitamin A will provide 50% of the EAR. Bioavailability of iron was originally assumed to be 5% for wheat, pearl millet, beans, and maize (10% for rice, cassava, and sweet potato), that of zinc 25% for all staple crops, and for provitamin A 8.5% for all staple crops (12 molecules of beta-carotene produce 1 molecule of retinol, the form of vitamin A used by the body).

Plant breeders screen existing crop varieties and accessions in global germplasm banks to determine whether sufficient genetic variation exists to breed for a particular trait. Initial research indicated that selection of lines with diverse vitamin and mineral profiles could be exploited for genetic improvement (Dwivedi et al., 2012; Gregorio, 2002; Ashok Kumar et al., 2012; Velu et al., 2012; Gomez-Becerra et al., 2010; Maziya-Dixon et al., 2000; Talukder et al., 2010; Jiang et al., 2008; Fageria et al., 2012; Menkir, 2008; Beebe et al., 2000; Montaserio and Graham, 2000; Menkir et al., 2008). Genetic transformation is an alternative method to incorporate specific genes that express nutritional density.

1.1.2. *Development*

Crop improvement includes all breeding activities. Initial product development is undertaken at international research institutes to develop varieties with improved nutrient content and high agronomic performance, as well as preferred consumer qualities. When promising high-yielding, high-nutrient lines emerge, they are tested by national research partners and the best-performing lines then selected to submit to national governments for release. The formal release process varies by country, but in general requires that a variety be grown and evaluated in several different locations (called multilocational trials) for at least two seasons, and its performance compared to other candidate and widely released varieties, before the national government approves the variety for dissemination. The breeding, testing, and release process can take 6–10 years to complete.

Parallel to crop improvement, nutrition research measures retention and bioavailability of micronutrients in the target crop under typical processing, storage, and cooking practices. Initially, relative absorption is determined using in vitro and animal models and, with the most promising varieties, by direct study in humans in controlled experiments. Randomized, controlled efficacy trials demonstrating the impact of biofortified crops on micronutrient status and functional indicators of micronutrient status (i.e. visual adaptation to darkness for provitamin A crops, physical activity for iron crops, etc.) provides evidence to support biofortified crops as alternative public health nutrition interventions.

Economics research on consumer and farmer evaluation of biofortified varieties, as well as varietal adoption studies, further informs crop improvement research during the development phase.