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The Potential Impact of Bio-fortified Crops for Improved Human Nutrition

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A New Paradigm for Agriculture

The proposed program aims to improve poor people's health by breeding staple food crops rich in micronutrients, a process referred to here as "biofortification." The Biofortification Challenge Program seeks to bring the full potential of agricultural and nutrition science to bear on the Persistent problem of micronutrient malnutrition. Micronutrient malnutrition, primarily the result of diets poor in bioavailable vitamins and minerals, affects more than half of the world's population, especially women and preschool children. The costs of these deficiencies in terms of lives lost, forgone economic growth, and poor quality of life are staggering. Billions of people in developing countries suffer from an insidious form of hunger known as micronutrient malnutrition. Even mild levels of micronutrient malnutrition may damage cognitive development, lower disease resistance in children, and reduce the likelihood that mothers survive childbirth.

History

Biofortification has existed since the Green Revolution (1966-1985) (Pingali 2012). An economist named Howarth Bouis started working on biofortification as a solution for micronutrient malnutrition in the early 1990s. After collaborating with scientists Robin Graham and Ross Welch, who secured early funding from the Danish International Development Agency (DANIDA) and the Australian Center for International Agricultural Research, screening to identify high-nutrient breeding parent plants began (Graham et al. 2001). In 2001, the bean researcher, Steve Beebe, coined the term 'biofortification'. In the following years, larger amounts of funding were secured from the Consultative Group on International Agricultural Research (CGIAR), the Asian Development Bank, the Bill and Melinda Gates Foundation, the World Bank, the US and UK governments and the European Union (EU). In 2003, CGIAR's Biofortification Challenge Program was renamed HarvestPlus (HarvestPlus 2018). Between 2003 and 2008, target populations were identified and proof-of-concept research conducted. Between 2009 and 2013, the first wave of biofortified crops was bred and approved for release by national varietal release committees, nutritional efficacy trials were carried out and delivery plans were developed. Since 2014, the delivery of biofortified crops has been scaled up and more than 140 varieties of ten crops that are biofortified with provitamin A, iron and/or zinc have been released in 30 countries and are being grown and tested in 60 countries in total. In some countries, just one biofortified crop is being used but in others, such as Brazil, India and China, several are used in what is known as a 'food basket' approach.

Advantages and disadvantages of biofortification in developing countries

Seeds for biofortified crops can be purchased and grown for the same cost as conventional crops, often at a higher yield due to inbred weather, pest and disease resistance, meaning no negative cost implications for farmers. Also, for predominantly subsistence farmers, there is the potential of a small surplus to sell and thereby to improve family living standards. Cuttings and seeds can normally be shared between farmers and used for generations, meaning this methodology is sustainable and the breeding process ensures sustainability of the chosen desirable traits, contributing to cost effectiveness. Furthermore, surplus food produced by farmers can be sold and potentially reach more communities but any health benefits identified cannot be extrapolated to non-farming communities, where intake of staple crops is likely to be lower. Although biofortification requires a large amount of investment up front by developers (to breed and test the crop), biofortified crops produced using government funding are public goods. Cost-effective analysis has demonstrated that biofortification is considerably cheaper than either fortification or supplementation approaches to tackle vitamin A deficiency, for example, in several countries (Asare-Marfo et al. 2014). There is likely to be a lag before any health benefits of a biofortified crop is realised due to the time needed to implement new crop strategies, for consumers to adopt new consumption patterns and for micronutrient status to improve. But over time, the consumption of a variety of biofortified foods could help to tackle multiple micronutrient deficiencies both through the 'food basket' approach and crops that are biofortified with more than one nutrient [e.g. iron and zinc pearl millet which is described in the section 'Iron (and zinc) pearl millet'].

Dietary diversity is the ultimate long-term solution to minimizing hidden hunger. This will require substantial increases in income for the poor so they are able to afford more nutritious nonstaple foods such as vegetables, fruits, and animal products.

Feasibility Studies Support An Expanded Global Research Program

Since 1995, scientists from four Future Harvest Centers of the Consultative Group on International Agricultural Research (CGIAR) and partner organizations have been evaluating the feasibility of using modern breeding techniques to produce new varieties of staple crops with high zinc, iron, and betacarotene content. Results to date suggest that biofortification is highly feasible. For most crops, scientists will be able to increase micronutrient densities through conventional breeding by a multiple of two for iron and zinc and by higher multiples for beta-carotene (vitamin A).

Biofortification: A New Tool to Reduce Micronutrient Malnutrition

Modern agriculture has had reasonable success in meeting the energy needs of developing countries. In the past 40 years, agricultural research in developing countries has met Malthus' challenge by placing increased cereal production at its center. However, agriculture must now focus on a new paradigm that will not only produce more food, but bring us better quality food as well.

By producing staple foods whose edible portions are more dense in bioavailable minerals and vitamins, a process referred to here as "biofortification," scientists can provide farmers with crop varieties that naturally reduce anemia, cognitive impairment, and other nutritionally related health problems in hundreds of millions of people. Biofortification can provide an additional instrument in the fight to reduce micronutrient malnutrition, one that uses food as a mechanism to improve human health.

Iron deficiency anemia is by far the most common micronutrient deficiency in the world. Iron deficiency during childhood and adolescence impairs physical growth, mental development, and learning capacity. In adults, iron deficiency anemia reduces the capacity to do physical labor. Iron deficiency increases the risk of women dying during delivery or in the postpartum period.

Zinc deficiencies have equally serious consequences for health. For example, meta-analyses of recent randomized controlled trials show that zinc supplementation can reduce morbidity from a number of common childhood infections, especially diarrhea, pneumonia, and possibly malaria, by one-third.

Vitamin A: Globally, approximately 3 million preschool-age children have visible eye damage owing to vitamin A deficiency. Annually, an estimated 250,000 to 500,000 preschool children go blind from this deficiency, and about two-thirds of these children die within months of going blind. Even more importantly, the last two decades have brought an awareness that vitamin A is essential for immune function.

Biofortification of staple crops

Fortification is the practice of deliberately increasing the content of an essential micronutrient, i.e. vitamins and minerals (including trace elements) in a food, so as to improve the nutritional quality of the food supply and provide a public health benefit with minimal risk to health. Biofortification is the process by which the nutritional quality of food crops is improved through agronomic practices, conventional plant breeding, or modern biotechnology. Biofortification differs from conventional fortification in that biofortification aims to increase nutrient levels in crops during plant growth rather than through manual means during processing of the crops. Biofortification may therefore present a way to reach populations where supplementation and conventional fortification activities may be difficult to implement and/or limited.

Examples of biofortification projects include:

- Iron-biofortification of rice, beans, sweet potato, cassava and legumes;
- Zinc-biofortification of wheat, rice, beans, sweet potato and maize;
- Provitamin A carotenoid-biofortification of sweet potato, maize and cassava; and
- Amino acid and protein-biofortification of sourghum and cassava.

Which biofortified crops are being utilised today and what are the health effects?

Biofortified crops currently used in developing countries largely contain enhanced levels of vitamin A, iron or zinc; examples are given in Table 1 Other biofortified crops such as banana/plantain, tomatoes, potatoes and pumpkin are under development (Mejia et al. 2017). A systematic review on the health effects of consuming biofortified foods is currently being undertaken on behalf of WHO (Garcia-Casal et al. 2016).

Crop	***Country***	***First year(s) of release***
Provitamin A maize	Zambia, Nigeria, Ghana, China	2012, 2012, 2012, 2015
Provitamin A cassava	Nigeria, Democratic Republic of Congo	2011, 2008
Provitamin A sweet potato	China, Uganda	2001, 2004
Zinc rice	Bangladesh	2013
Zinc wheat	India	2014
Iron beans	Rwanda, Democratic Republic of Congo	2010, 2011
Iron pearl millet	India	2012
Iron and zinc lentils Iron cowpea	India, Nepal, Bangladesh India	2012, 2013, 2013, 2008

Source: HarvestPlus (2014).

Table 1: Examples of biofortified crops and their respective dates and countries of release.

Golden Rice

In a victory for science-based regulatory decision-making, the Government of the Philippines has, on 10th December 2019, authorized the direct use of GR2E Golden Rice in food, feed, and for processing. The regulatory data were submitted by the Philippine Rice Research Institute (PhilRice) and the International Rice Research Institute (IRRI) in the spring of 2017 and were scrutinized by several regulatory committees representing agriculture, environment, health, science and technology, and local governments. This decision is huge, representing the first food approval for Golden Rice in a country where rice is the staple and vitamin A deficiency a significant public health problem. Those involved in the authorization are to be praised for their scientific integrity and courage in the face of stiff activist opposition.

In taking their decision, the Philippine Government has joined Australia, Canada, New Zealand, and the USA in affirming that Golden Rice is perfectly safe. (Swamy et.al.,2019).

Mean provitamin A concentrations in milled rice of GR2E can contribute up to 89–113% and 57–99% of the estimated average requirement for vitamin A for preschool children in Bangladesh and the Philippines, respectively.

Biofortification: Empowering and Self-sustaining

The 2016 World Food Prize has been awarded to the group of scientists who have tirelessly worked on breeding and introducing orange-fleshed sweet potatoes to Africa and thus benefitting millions of people, especially children, who are most susceptible to a lack of provitamin A. The World Food Prize thus once again recognises efforts to increase the quality and quantity of available food to the most vulnerable populations in the world.

Three of the 2016 laureates - Drs Maria Andrade, Robert Mwanga and Jan Low are from the CGIAR International Potato Center (CIP). The fourth winner, Dr Howard Bouis, is the founder of HarvestPlus at the CGIAR International Food Policy Research Institute (IFPRI), and is being recognised for his work over 25 years to ensure biofortification was developed into an international plant breeding strategy across more than 40 countries.

Vitamin A deficiency (VAD) is considered to be one of the most harmful forms of malnutrition in the developing world. It can cause blindness, limit growth, and weaken the body's immune system, thereby increasing morbidity and mortality. The condition affects more than 140 million pre-school children in 118 nations, and more than seven million pregnant women. It is probably the leading cause of child blindness in developing countries.

Biofortification seeks to improve nutritional quality of food crops (K. H. Brown,1991) through agronomic practices, conventional plant breeding, or modern biotechnology, as in the case of Golden Rice. The approach of providing farmers with biofortified crops, indepedently of the technology used to achieve it, is thus the most efficient way of creating a self-sustaining and virtuous cycle of nutritional independence and life quality improvement.

Biofortified rice as a contribution to the alleviation of life-threatening micronutrient deficiencies in developing countries: A good start is a food start!

Dietary micronutrient deficiencies, such as the lack of vitamin A, iodine, iron or zinc, are a major source of morbidity (increased susceptibility to disease) and mortality worldwide. These deficiencies affect particularly children, impairing their immune system and normal development, causing disease and ultimately death. The best way to avoid micronutrient deficiencies is by way of a varied diet, rich in vegetables, fruits and animal products.

The second best approach, especially for those who cannot afford a balanced diet, is by way of nutrient-dense staple crops. Sweet potatoes, for example, are available as varieties that are either rich or poor in provitamin A. Those producing and accumulating provitamin A (orange-fleshed sweet potatoes) are called *biofortified*,* as opposed to the white-fleshed sweet potatoes, which do not accumulate provitamin A. In this case, what needs to be done is to introduce the biofortified varieties to people used to the white-fleshed varieties, as is happening at present in southern Africa by introducing South American varieties of orange-fleshed sweet potatoes.

Bio fortified staple crops such as provitamin A-bio fortified sweet potato ('orange sweet potato'), zinc-bio fortified rice ('zinc rice'), and iron-biofortified beans ('iron beans'), developed by selective breeding, have been introduced into developing countries to reduce micronutrient deficiencies.

The process of breeding such nutritious crops requires addressing three questions:

1. Can higher levels of a nutrient be bred into the crop without harming other desirable agronomic traits like yield?

2. Can consumers absorb the extra nutrients—and does this improve their health?
3. Are farmers and consumers willing to adopt the biofortified crop?

"By now we have more than 300 varieties of all those crops, released in more than 35 countries," said Pfeiffer. "More than 50 million people are already consuming those crops."

Nutritional security through crop biofortification in India: Status & future prospects: Malnutrition has emerged as one of the most serious health issues worldwide. The consumption of unbalanced diet poor in nutritional quality causes malnutrition which is more prevalent in the underdeveloped and developing countries. Deficiency of proteins, essential amino acids, vitamins and minerals leads to poor health and increased susceptibility to various diseases, which in turn lead to significant loss in Gross Domestic Product and affect the socio-economic structure of the country. Although various avenues such as dietary-diversification, food-fortification and medical-supplementation are available, biofortification of crop varieties is considered as the most sustainable and cost-effective approach where the nutrients reach the target people in natural form. Here, we have discussed the present status on the development of biofortified crop varieties for various nutritional and antinutritional factors. (Devendar Kumar et.al.,2018).

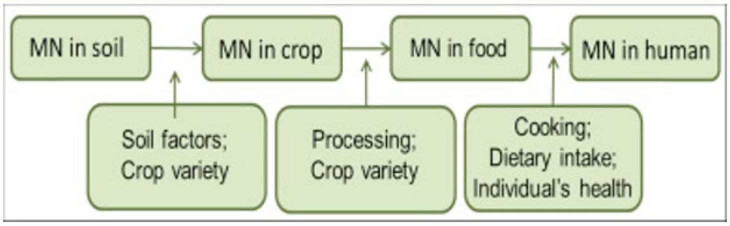

Figure 1: Schematic overview of micronutrient (MN) pathway from soil to humans and the factors that influence MN bioavailability to the next level. Based on Mayer et al. (2011).

Biofortified crops for tackling micronutrient deficiencies - what impact are these having in developing countries and could they be of relevance within Europe?

The development of crops that by harvest have accumulated higher amounts of a particular micronutrient than standard crops is known as biofortification. Biofortified staple crops such as provitamin A-biofortified sweet potato ('orange sweet potato'), zinc-biofortified rice ('zinc rice') and iron-biofortified beans ('iron beans'), developed by selective breeding, have been introduced into developing countries with the goal of reducing micronutrient deficiencies. In these settings, micronutrient deficiencies caused by low dietary intakes and exacerbated by inflammation and infection result in considerable morbidity and mortality worldwide. The aim of this review is twofold: (1) to describe the impact of biofortified crops on micronutrient intake, nutritional status and other biological endpoints in developing countries and (2) to consider the relevance of these nutritional effects in other parts of the world such as Europe. Regular consumption of biofortified crops in developing countries where micronutrient deficiency is common has been shown to increase micronutrient intakes and thus help meet the World Health Organization's dietary recommendations. In terms of micronutrient status, most research has been conducted using provitamin A-biofortified crops (particularly orange sweet potato), with large 2- to 3-year studies indicating increases in plasma retinol, though additional studies measuring change in body stores would provide more definitive evidence. There is some evidence to suggest that iron-biofortified crops can increase iron status (measured by serum ferritin and total body iron), but further studies are required to demonstrate the efficacy of zinc-biofortified foods. Intakes of some micronutrients are low in some UK population subgroups (in particular adolescents and young adult women), with sizeable proportions having intakes below the lower reference nutrient intake. There is also evidence of low status for some nutrients (e.g. iron and in particular vitamin D), although the prevalence of iron deficiency is much less, and therefore the consequences less severe, than seen in the developing world. The final part of the paper describes strategies used to improve micronutrient intake in Europe, such as fortification of bread flour post-harvest and supplementation with vitamin D and folic acid, and discusses whether there is a role for biofortified crops in the UK.

Biofortification - enhancing the micronutrient concentration of staple crops - offers a sustainable solution to hidden hunger

An incredible 155 million children around the world are chronically undernourished, despite dramatic improvements in recent decades. In view of this, the UN's sustainable development goals include zero hunger. But what do we understand by the word hunger?

It may refer to lack of food or widespread food shortages caused by war, drought, crop failure or government policies. But as researchers we are particularly interested in a different kind of hunger - one that is less visible but equally devastating.

Micronutrient deficiencies, also known as hidden hunger, occurs when there is a lack of essential vitamins and minerals in a person's diet. This condition affects more than two billion people globally, and can contribute to stunted growth, poor cognitive development, increased risk of infections and complications during pregnancy and childbirth. The wider impacts of micronutrient deficiencies socially and economically are also well established.

Supplementation and food fortification have long been used around the world to alleviate micronutrient deficiencies. Both strategies boast high cost/benefit ratios. But as they require repeated investment, their sustainability is limited. Supplements may be used to treat multiple micronutrient deficiencies, but this is a resource-intensive approach and does not address the cause of the problem - dietary inadequacy.

Food fortification, on the other hand, improves the nutritional quality of food itself. Here, micronutrients are added to commonly consumed foods at the processing stage. This strategy can be implemented at population level, and does not require individuals to change their eating behaviors.

In the UK, for example, flour has been fortified with calcium since the Second World War, when a reduced supply of dairy products was anticipated. Today, many of our foods are fortified, including bread, cereal products and fat spreads.

In developing countries, food fortification has gained momentum in recent years through the work of organisations such as the Global Alliance for Improved Nutrition (Gain). Large-scale food fortification programmes have enhanced the micronutrient content of a range of staple foods in more than 30 countries. For example, the Gain/Unicef universal salt iodisation partnership has protected 466 million people in 14 countries against the debilitating effects of iodine deficiency - such as mental impairment and goitre, a swelling in the neck resulting from an enlarged thyroid gland.

But one major disadvantage of food fortification is that some of the poorest families may not have access to commercially processed foods. And it is these remote rural communities - that grow and process food locally - that are often the most affected by hidden hunger. Biofortified crops include vitamin A maize, vitamin A cassava, vitamin A sweet potato, iron beans, iron pearl millet, zinc rice and zinc wheat. These crops have been introduced into many countries in Africa, Asia and Latin America.

Biofortification has several advantages over food fortification. After the initial investment to develop the biofortified seed, it can be replicated and distributed without any reduction in the micronutrient concentration. This makes it highly cost-effective and sustainable. Biofortified crops are also often more resilient to pests, diseases, higher temperatures and drought - essential qualities as many countries become increasingly susceptible to climate change. And, perhaps most importantly for nutrition, biofortified crops reach the world's poorest and most vulnerable people.

Each new biofortified crop requires meticulous development and evaluation to ensure the micronutrient concentration is sufficient to make a significant impact on nutritional status, and that farmers and consumers will adopt the new biofortified varieties. Research has shown high levels of consumer acceptance, especially when information and awareness campaigns were implemented.

Micronutrient Malnutrition: A Hidden Hunger

Experts estimate that 2 billion people, mostly in poorer countries, suffer from micronutrient malnutrition, also known as hidden hunger.1 This is caused by a lack of critical micronutrients such as vitamin A, zinc, and iron in the diet. Hidden hunger impairs the mental and physical development of children and adolescents and can result in lower IQ, stunting, and blindness; women and children are especially vulnerable. Hidden hunger also reduces the productivity of adult men and women due to increased risk of illness and reduced work capacity. One study cited in the Lancet series found that men who had received nutrition supplements (that included micronutrients) from ages 0-36 months earned a higher hourly wage than men who had not received the supplements.

Nutritionists must determine the additional amount of a nutrient a food crop must provide to measurably improve nutrition when that crop is harvested, processed or cooked, and eaten. To do so, nutritionists must account for 1. nutrient losses after the crop is harvested (nutrients can degrade substantially during storage, processing, or cooking), 2. the amount of the nutrient that the body actually absorbs from the food (bioavailability), and 3. the amount of the staple food actually consumed on a daily. (Howarth et. al., 2010).

Of course, biofortification is a partial solution, which must go hand in hand with efforts to reduce poverty, food insecurity, disease, poor sanitation, social and gender inequality. But it has the potential to contribute to the eradication of hidden hunger, and the UN's aim to end all forms of hunger and malnutrition by 2030. Biofortification will emerge as an agriculture-based strategy that helps to meet the nutritional needs of malnourished communities throughout the world.

Future prospects: Intensive efforts by public sector institutions and policy for intense promotional campaigns can effectively ensure a significant increase in the adoption and acceptance of biofortified crop varieties. Strengthening the seed chain to produce and supply good quality seeds is one of the important steps for the popularizing biofortified varieties. The maintenance of genetic purity is very essential for keeping the quality trait intact; hence, special seed production areas need to be identified. Seed village program can also be one option for taking the seed/commercial production of such varieties to avoid outcrossing from other conventional varieties. Providing subsidized seeds and other inputs would further contribute to the rapid dissemination of nutritionally improved cultivars among the farmers. Assured premium remunerative price through minimum support price for biofortified grains in the market will encourage the farmers to grow more biofortified crops. Investment on extension activities would make the farmers, industry and consumers aware of the availability and benefits of biofortified crops. Essential interventions required for research, development and popularization of biofortified crop varieties is the need of the hour. Government is promoting adoption of smart farming methods through the use of technology and innovation in the agriculture sector in the country. Government is implementing a Digital Agriculture Mission (DAM) which includes India Digital Ecosystem of Agriculture (IDEA), Farmers Database, Unified Farmers Service Interface (UFSI), Funding to the States on the new Technology (NeGPA), Revamping Mahalanobis National Crop Forecast Centre (MNCFC), Soil Health, Fertility and profile mapping. Under the NeGPA programme funding is given to State Governments for Digital Agriculture projects using emerging technologies like Artificial Intelligence and Machine Learning (AI/ML), Internet of Things (IOT), Block chain etc. Adoption of drone technologies is being done. To promote smart farming, the Government promotes Startups in the Agriculture sector and nurtures agri-entrepreneurs. The Per Drop More Crop component of the Pradhan Mantri Krishi Sichai Yojana (PMKSY-PDMC) aims to increase water use efficiency at the farm level through micro irrigation technologies, i.e., drip and sprinkler irrigation systems. The GoI started eNAM (National Agriculture Market), an electronic trading portal which creates networks between the existing Agricultural Produce Market Committee (APMC) mandis for the farmers.

The Indian Council of Agricultural Research (ICAR) promotes innovation, extension and education in agriculture. A total of 1575 field crop varieties were released for different agricultural crops during 2014-21. During 2014-21, 91.43 crore Agro-advisories were provided to farmers through mobiles. ICAR developed 187 mobiles apps on different farm and farmer related services during 2014-21. These ICAR apps are now integrated on one common platform called KISAAN. The Farmer FIRST (Farm, Innovations, Resources, Science and Technology) initiative was launched during this period by ICAR with enhanced farmers-scientists interface to move beyond production and productivity.

This information was given by the Union Minister of Agriculture and Farmers Welfare, Shri Narendra Singh Tomar in a written reply in Rajya Sabha today.

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