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THE BIOFORTIFICATION CONTINUUM: IMPLICATIONS FOR FOOD AND NUTRITION SECURITY IN DEVELOPING COUNTRIES

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ABSTRACT

Addressing vitamin and mineral status of communities has presented challenges to governments and health experts across the globe. These nutrient deficiencies are commonly referred to as 'hidden hunger' because their symptoms are not visible to the naked eye. Dietary diversity, food fortification and micronutrient supplementation are the three main strategies used for addressing this problem. Because most people in developing countries rely on plant-based diets, biofortification presents an opportunity for addressing vitamin and mineral deficiencies. Although fortification and supplementation are effective in specific target populations, biofortification increases food nutritional value in the dietary diversity option. Supplementation is expensive and requires linkages with health programs such as polio immunization to minimize costs. Food biofortification requires not only laboratories but other facilities to carry out the process. Food fortification also requires a well-equipped laboratory to monitor quality at the factory level and ensure product success in the market. While biofortification is expensive in the beginning, it is more cost-effective and stable in the long run. Supplementation has been done in partnership with UNICEF for iron and folic acid for expectant mothers, as well as vitamin A supplementation for children aged 6-59 months and lactating mothers. Calcium supplementation is also done in some countries for pregnant women. Food fortification is done to edible oils (vitamin A), grain flour (maize and wheat) and complementary foods. Fortification of edible oils with vitamin A and fortification of flour with iron and other micronutrients has been mandatory in Kenya since 2012. Additionally, the Ministry of Health (MoH) developed guidelines for home-based fortification (sprinkles) in 2014/2015. Micronutrient supplementation and food fortification have achieved varied degrees of success in Kenya according to the 2011 National Micronutrient Survey. Biofortification may provide considerable amounts of readily bioavailable micronutrients. As outlined in this paper, biofortification offers a fresh approach to addressing vitamin and mineral deficiencies mainly due to affordability and accessibility. Although salt iodization is mandatory at 30-50 mg/kg, less than 50% of the salt manufacturers have complied with these requirements, indicating the complexities of food fortification.

Key words: fortification, supplementation, biofortification, iron, vitamin A, zinc, *phytochemicals*, cost-effectiveness

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INTRODUCTION

Vitamin and mineral deficiencies are a major cause of morbidity and mortality mainly in the developing world. One of the added accelerators to ending malnutrition in the world is technology. With increasing populations and the triple burden of disease (micronutrient deficiency, over and under-nutrition), technology remains one of the most viable options for addressing poor nutrition. From the technological perspective, biofortification is a cost-effective and sustainable technology to achieve the micronutrient malnutrition objective [1,2]. Globally, three strategies of addressing vitamin and mineral deficiency are employed: dietary diversity, fortification and supplementation. Food bio-fortification, which falls under the dietary diversity category, is cheaper than adding micronutrients to already processed foods or micronutrient supplementation [2,3,4].

People living in poor- resource settings are likely to benefit more from food biofortification than other strategies [1,3]. Human diets often lack one or more essential nutrients. Poor quality diets characterized by high intakes of plant-based foods and low consumption of animal source diets (meat and fish), fruits, legumes, and vegetables (all rich sources of bioavailable minerals and vitamins) cause vitamin and mineral deficiency [5]. According to the United Nations (UN), more than half of the world's population suffer micronutrient undernourishment (most affected being preschool children and women) [5,6,7].

The human body requires more than 20 mineral elements and more than 40 nutrients, particularly vitamins and essential amino acids, all of which can be supplied by the appropriate diets. Due to a combination of high levels of vitamin and mineral deficiencies and starch shortages in developing countries, crop biofortification, therefore, plays a cheaper and significant role in addressing food security and hidden hunger related problems. Cassava, for instance, is a staple food in Africa, South America and South East Asia and could serve as a suitable agent for biofortification [1, 2, 3].

Zinc (Zn), iron (Fe), and vitamin A deficiency are ranked 5th, 6th, and 7th, respectively, among the top ten risk factors contributing to the burden of disease in lower income economies. In developing countries there is high child and adult mortality [7]. In the last decade, significant progress has been made in the international crop breeding community to boost the nutrient concentration of staple crops [2,7]. Among the achievements attained is conventional breeding efforts, which have resulted in the development of varieties of several staple food crops with significantly increased levels of these three micronutrients that are the most limiting in diets [1,6,7]. In response to climate change, biofortification presents an option for developing countries, including those in Africa, to add value to readily available and accessible crops such as sorghum, cassava, and sweet potatoes [2,8,9]. Biofortification additionally offers an opportunity to more than 15 million people in developing countries to grow nutrient-rich crops and consume healthy diets [8].

In comparison to other strategies, biofortification requires a one-time investment in dissemination of varieties with the nutrient-dense trait. It is meaningful because the

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nutrient-dense varieties are self-sustaining and additional costs are not necessary [1,2]. Food biofortification, which uses a number of techniques, including plant breeding to enhance the micronutrient content of staple foods, is a new complementary approach to addressing vitamin and mineral deficiencies in resource-poor settings [10].

Key micronutrients under consideration
Various projects have been implemented in Kenya, through the government's institutions of higher learning and agricultural and livestock research. Food-based interventions focus on addressing food accessibility, including alleviating multiple vitamin and mineral deficiencies in susceptible populations. These strategies have advantages over other options because they can provide a sustainable source of a variety of nutrients and other *phytochemicals* without the recurring transport and administration costs of other methods [11,12]. Vitamin A deficiency is a leading cause of morbidity and mortality, especially in young children, pregnant and lactating women. Vitamin A deficiency (VAD) for children aged less than five years has increasingly been addressed through supplementation (100,000 IU for 6 - 11 months, and 200,000 IU for 12 - 59 months) [13-15].

Research institutions have initially focused their efforts on the development of Zn-fortified wheat (*Triticum aestivum L.*) and rice (*Oryza sativa L.*); iron-fortified pearl millet (*Pennisetum glaucum L.*) and common bean (*Phaseolus vulgaris L.*) [7,9,10]. Consumption of millet was and still is common among members of the Kamba community in Kenya (popularly known as *kiteke* [1]) and might, therefore, be an appropriate vehicle to deliver starch and iron for this and other communities. Research is currently underway regarding the vitamin A efficacy of orange cassava in Nigeria and Kenya. Biofortification breeding is also ongoing to develop Zn-rich maize (*Zea mays L.*) and cowpea (*Vigna unguiculata L.*) [10]. Because the World Health Organization (WHO) classifies iron, zinc and vitamin A as micronutrients of public health importance, the aim of biofortification is to increase these micronutrient dietary intakes without changing the diet of targeted populations [11].

Vitamin A deficiency (VAD) has continued to be a problem of public health significance despite some successes in two key implementation programs of vitamin A supplementation (capsules of 100,000 IU and 200,000 IU) and point of use fortification (multiple micronutrient powders with 300 µg retinol). Vitamin A deficiency has been linked to adverse health consequences such as night blindness, corneal scarring and blindness [6,7]. Vitamin A deficiency (VAD) also weakens the immune system, consequently increasing infant mortality and the incidence and severity of infectious diseases [4,14]. Vitamin A deficiency is estimated to cause an annual global mortality of approximately one million children [11]. The number of children under 5 years with compromised immune systems linked to VAD is estimated at 30% in the lower income economies [4]. Vitamin A deficiency in children is associated with an estimated 20% of measles-related mortality, 24% of diarrhea mortality, 20% of malaria incidence and mortality and 3% of mortality related to other infectious causes across the globe [10,14].

[1] Traditional relish among members of the Kamba community in Kenya.

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Vitamin A deficiency also affects women and is associated with over 20% of maternal mortality. The highest burden of disease related to VAD and maternal mortality is found in South Asia and Africa [4,15].

Iron deficiency is among the most common nutrient deficiencies in the world, affecting estimates of more than two billion people [4,16,17]. Similar to VAD, iron deficiency anemia (IDA) commonly affects preschool age children and women [18,19]. Consequently, iron deficiency anemia is linked to maternal and perinatal mortality, and impairment of cognitive skills and physical activity [18-21]. Unfortunately, IDA is disproportionately prevalent in South Asia and Africa where 43% and 37%, respectively, of maternal mortality are attributed to IDA [19]. In areas where diets are predominantly plant-based, these population groups are potentially at higher risk.

Zinc deficiency in Kenya for preschool age children is estimated at 83.3% [16], a problem of severe public health significance according to the WHO [14]. The Kenyan situation is worse than global Zn deficiency estimates at 31% [11,16]. The most severe burden of diarrhea and pneumonia due to Zn deficiency is found in Africa and South Asia [17]. Malaria disease is also affected by Zn deficiency in African populations [11]. The disease burden due to Zn deficiency is equally borne between males and females [12]. According to research, there was a positive correlation between stunting and Zn deficiency [16]. Although Zn is used in many countries for treatment of diarrhea diseases, these countries have high levels of deficiency [11]. Zn is an essential micronutrient influencing gene expression, cell development and replication. A mortality rate of close to a million children annually is attributable to Zn deficiency because it is associated with the prevalence of diseases such as diarrhea, pneumonia, and malaria [21].

Why biofortification?

People living in developing countries have predominantly plant-based diets, which lead to VAD and iron deficiency [12,13]. It is estimated that biofortification, such as iron-fortified beans could provide up to 80% of the estimated average requirement (EAR) for non-pregnant, non-lactating women of reproductive age upon meeting the breeding target concentrations [2,3]. Conventional plant-breeding techniques that use phenotypic and/or marker-assisted selection have proven to be successful in generating variants with enhanced micronutrient content [21-23].

Food-based interventions focused on addressing food accessibility, including alleviating vitamin A deficiency in susceptible populations have advantages over supplementation and fortification, because they can provide a sustainable source of a variety of nutrients and other *phytochemicals* without the recurring transport and administration costs of these other methods [1-3]. Most of the disability-adjusted life years (DALYs) due to VAD come through either mortality or morbidity and occur virtually in children aged less than five years [1,2]. Nyanza and Eastern regions in Kenya account for more than 80% of sorghum produced. This has further been enhanced by the government's partnerships with a local alcohol company where farmers are contracted to produce sorghum for beer production [23-25].

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Similar to cassava and sweet potatoes, sorghum is traditionally perceived as an inexpensive staple food crop that offers low returns for producers in Kenya. These grains are generally considered as not traded or are primarily traded locally. The Kenyan government's partnership with East African Breweries has introduced a "cost" aspect to these "poor man's" cereal crop [26]. Additionally, domestic sorghum consumption has steadily increased (used in weaning food and flour), which has led to opening new marketing channels. Sorghum, therefore, has the potential to offer higher returns for farmers [24,25]. Thus, sorghum grains that have been biofortified with iron are likely to add nutritional value to consumers' diets.

Evidence from nutrition research shows that biofortified varieties provide considerable amounts of bioavailable vitamins and minerals, and consumption of these varieties can improve vitamin and mineral status among target populations [2,3]. Farmer adoption and consumer acceptance research shows that farmers and consumers prefer the various production and consumption characteristics of biofortified varieties, as much as (if not more than) popular conventional varieties, even in the absence of nutritional information. A good example is the adoption of orange-fleshed sweet potatoes (OFSP) in Kenya where they are available in some parts of the country (such as Embu county and virtually absent in others such as Nairobi county). Availability of OFSP has been increased by scientists from these areas, who work with the Kenya Agricultural and Livestock Research Institute (KALRO) [3].

Further development and delivery of these vitamin and mineral-rich varieties can potentially reduce hidden hunger, especially among rural populations. Future work should include strengthening the supply and the demand for biofortified staple food crops and facilitating targeted investment to those crop–country combinations that have the highest potential nutritional impact [24,25].

Advantages of biofortification

Hidden hunger has a negative effect on human productivity and economic growth and development [12]. These deficiencies occur when bio-accessibility and bio-availability of vitamins and minerals are not in line with recommended dietary allowances (RDA) [13,14].

Over the past few decades, research in agriculture has increased production and availability of nutrient dense staple crops [1,2]. However, the production of micronutrient-rich non-staples like vegetables, pulses and animal products, has not increased in equal measure. Satisfaction of adequate nutrition is enhanced by food availability and accessibility. Due to the ever increasing populations, the non-staple food prices have increased steadily and substantially, making it more difficult for the poor (the very same persons with high fertility rates) to afford quality diets [8]. In the long-term, increased production of micronutrient-rich foods and improving dietary diversity is envisaged to substantially reduce micronutrient deficiencies [8]. In the short-term, consumption of biofortified crops could help address micronutrient deficiencies by increasing the daily adequacy of micronutrient intakes among individuals throughout the lifecycle [8,9].

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Unlike food supplementation and fortification programs, which require continuous financial requirements, biofortification requires an upfront investment in plant breeding which yields micronutrient-rich biofortified planting material for farmers to grow at virtually zero marginal cost. The OFSP project has been completed in Kenya by the International Potato Center (CIP) and other development partners through KALRO. The Kenyan government is increasing OFSP coverage, which is aimed at addressing vitamin A status of populations at marginally minimum costs. The orange fleshed cassava project is ongoing in lower eastern sections (KALRO, Makindu) of the country. Members of the Kamba community use cassava in boiled form while their counterparts in Western Kenya mix dry cassava with sorghum to produce flour for stiff porridge (locally known as *ugali in the Kiswahili language*). Upon development, nutritionally improved crops will be evaluated and adapted to new environments and geographies, multiplying the benefits of the initial investment. Rural populations have limited access to diverse diets or other micronutrient interventions. Biofortified crops are a possible and feasible means of reaching these populations. According to Kenya's national micronutrient survey, vitamin A deficiency in pre-school age and school age children was higher in urban, compared to rural areas, where persons have a higher access to fruits and vegetables [16,38]. Once the micronutrient trait has been mainstreamed into the core breeding objectives of crop development programs, recurrent expenditures by agriculture research institutes for monitoring and maintenance requirements will be minimal.

Fortification and supplementation are shorter term and more expensive public health interventions that are more appropriate for acute cases of micronutrient deficiency [3,8]. Despite the mandatory requirements for fortification of centrally processed maize meal with vitamins and minerals, the Kenyan government has not been able to adequately address iron deficiency. Persons with high levels of iron deficiency consume whole meal (greater than 60% of the Kenyan population). Secondly, flour fortification players have not been able to fortify their maize flour in accordance with government requirements of 20 mg/kg [16].

Addressing iron status through supplementation: iron and folic acid supplements (IFAS) have not been successful due to a number of challenges (including logistics). There are plans to spread the IFAS project to adolescent girls. However, IFAS might not be successful in men and children younger than 6 years (because they are not the targeted populations). An attempt to address the problem through micronutrient powders has hit cost challenges. Affected communities might not be able to afford the micronutrient powders. Iron-rich millet might help alleviate some of the problems at relatively low costs [11].

Vitamin A supplementation only addresses children younger than five years and is effective in communities with high exclusive breastfeeding levels (greater than 90%). By its own, vitamin A supplementation is expensive and its feasibility lies on linking to health programs such as polio immunization because it is not sustainable as a human nutrition program in ministries of health [26,27].

The two strategies (fortification and supplementation) require infrastructure, sophisticated processing technology, and product control, purchasing power, market

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access and efficient health care systems for their success. Food fortification might not be available for people living in remote areas. Biofortification on the other hand targets low-income households, capitalizing on regular daily intake of staples, such as sorghum, cassava, beans and sweet potatoes. Because developing countries are faced with serious infrastructural challenges, biofortification is likely to reach the rural poor areas [2,3,27]. Biofortification is a powerful intervention tool for macro and micronutrients; it is a one-time investment with low recurrent costs. The biofortification process relies on the plant's biosynthetic (vitamins) or physiological (mineral) capacity. The criteria for biofortification include: crops must be high yielding (crop productivity must be maintained/enhanced to guarantee farmer acceptance); effective (micronutrient enrichment levels must have significant impact on human health); enriched levels must be relatively stable; the nutrients must be efficacious (the enriched foods must be tested in humans to ensure that they improve the micronutrient status of people preparing and consuming them); and the products must be acceptable to the consumers (taste and cooking quality) [2,3]. Biofortification requires direct linkages between agricultural researchers and various specialists like nutritionists, public health officials, sociologists, political scientists, food technologists and economists [27].

Cost-effectiveness of Biofortification

Using DALY, the cost-effectiveness of biofortified foods has been proven [1,18]. The debate about cost-effectiveness and an open discussion about biofortification should be encouraged as one of the strategies for addressing vitamin and mineral deficiencies. This discussion should compare the three strategies for addressing hidden hunger.

Addressing the vitamin and mineral deficiency problem will assist in attaining some of the Sustainable Development Goals. The first five sustainable development goals include: end poverty in all its forms everywhere; end hunger, achieve food security and improved nutrition to promote sustainable agriculture; ensure healthy life and promote well-being for all at all ages; ensure inclusive and equitable quality education and promote lifelong learning opportunities for all; achieve gender equality and empower all women and girls. The increase in poverty levels, poor child and maternal health care, have been caused by an ever increasing population per hectare of land globally [28-32]. This has consequently led to an exponential increase in the number of people living without adequate diets. Food biofortification could be effective in improving DALYs [2,33,34]. It would be useful to adopt new technologies to increase the quality of diets for the increasing populations and therefore, improve quality of life [19]. WHO [14] uses ingredients-approach for calculating cost-effectiveness. On the contrary, biofortification utilizes agronomic intervention or genetic modification for selection of crop plants to increase the bioavailable concentration of a component [30].

Compared to food fortification which requires access and affordability of processed foods, biofortification increases the micronutrient density of dietary staples, such as rice, potatoes, wheat, maize, and beans, making them more accessible to communities living in remote areas [28,29]. However, if confused with genetic modification, biofortification could generate more negative than positive opinions counteracting the potential health benefits. This should be addressed by researchers to increase farmers' and consumer acceptability because if not accepted, it would be difficult to address the hidden hunger

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problem. Despite poor micronutrient density of white corn, Kenyans will not consume yellow maize, although nutritionally beneficial (rich in carotenoids and other micronutrients). The meal from white maize is more often highly refined, getting rid of the corti cells that play a critical role on nutrient content of the cereal grain. Studies on orange corn have been undertaken in Zambia where it might be used to address VAD in addition to other foods/strategies. However, yellow maize had less beta-carotene before biofortification [6,30,31]. In the implementation of biofortification, critical consideration should be infrastructural capacities of the countries [32,33]. Whereas it might be applicable in India, the application in sub-Saharan African countries could be more difficult, due to low acceptability and poor infrastructure [33].

Improved health is more important than concerns with the biofortification strategy. Therefore, countries should engage citizens to produce foods with high nutrient density to promote health. Increasingly, developing countries have produced food consumption data that excludes assumptions during research for biofortified foods. Unfortunately, these consumption databases might not be valid and they coexist with other programs. Dietary diversity might be a cost-effective way of addressing vitamin and mineral deficiencies. However, this may be confounded by factors such as availability of land, amount of water, fertility, and technological knowledge. Addressing hidden hunger cannot be achieved in isolation [35,36]. Therefore, improved partnerships are important between plant breeders and nutritionists to increase production of more nutrient-dense products. Addressing these assumptions will lead to a more valid decision on the cost-effectiveness of biofortification [2,3].

In measuring up to the challenge of sustainable increases in vitamins and minerals, biofortification addresses social-economic and social-political needs, thus contributing towards equitable development. To face the resistance to biofortification, scientists and governments should reassure farmers that biofortification uses traditional breeding practices, with more precision and will not lead to a decrease in their harvest [30]. In terms of resources, biofortification is one of the most cost-effective strategies. Once the farmers are provided with seeds, they continue with production without any further support [36].

There are challenges faced by nutritionists to determine and demonstrate the ability of biofortified crops to have an impact on the nutritional and health status of target populations. These challenges include: effect of biofortified products on infections and on efficacy; adequate and sensitive biomarkers of micronutrient status; desirable agronomic traits bred into biofortified staples; functional seed extension systems for distribution; consumer acceptability if sensory characteristics are altered (for instance orange color due to beta-carotene); and successful demand creation. Recommendations for addressing these challenges are provided. Compared to protein content, micronutrient density traits are stable across environments and, therefore, crops may be grown in different areas of the world without affecting productivity [10,32,33]. However, crop and environment-specific traits relevant to adoption should be considered in the breeding strategy for biofortified crops and end-product definition. For example, seed zinc concentration in wheat is closely related with stand establishment and final grain yield in zinc-deficient soils.

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However, this strategy may draw both positive and negative opinions and consumer and farmers' choices should be carefully guided to avoid drawbacks in the success made thus far. Readers should make their own opinion(s) regarding this issue. Two factors are critical to farmer adoption, namely whether the trait is visible (for instance color change in sweet potatoes, cassava and corn) and infrastructural development. Lack of sensory change in the biofortified product will not lead to negative influence for the product. More studies need to be done to corroborate the existing evidence on cost-effectiveness of nutrition biofortification on more staple foods, under different settings [2,3].

Addressing vitamin-mineral deficiencies through food biofortification
Human diets often lack one or more essential vitamins and minerals because of plant-based staples [5]. The content of minerals and vitamins can be increased through plant breeding. Biofortification holds great promise for improving the nutritional status and health of poor populations in both rural and urban areas of the developing world. Target micronutrient levels for biofortified crops are set to meet the specific dietary needs of women and children, based on existing consumption patterns. Biofortification puts a solution in the hands of farmers, combining the micronutrient trait with other agronomic and consumption traits that farmers prefer [3,4]. After fulfilling the household's food needs, surplus biofortified crops make their way into rural and urban retail outlets.

Cost-effectiveness
Ex-post cost-effectiveness data are currently available for OFSP in Uganda, where biofortification was demonstrated to cost US$15–$20 per DALY saved [2,3]. Results of *ex-ante* cost-effectiveness studies have shown that for each of the country-crop-micronutrient combinations considered, biofortification is a cost-effective intervention based on cost per DALY saved, using World Bank standards [22]. Furthermore, the Copenhagen Consensus ranked interventions for reducing micronutrient deficiencies, including biofortification, among the highest value-for-money investments for economic development [22]. For every dollar invested in biofortification, as much as US$17 of benefits may be gained [22,23]. The cost-effectiveness of any given intervention is dependent on the crop, micronutrient, and country of delivery.

CONCLUSION

Understanding population diets is key in the determination of the strategy for addressing hidden hunger. However, this is not possible without close collaborations among different stakeholders mainly those working on the agriculture and nutrition arena. Focusing on supplementation and food fortification might not effectively address micronutrient deficiency in resource poor settings leading to increased DALYs and consequently compromising the health of the population. This does not denigrate these strategies in addressing vitamin and vitamin status of various persons. While aiming at generating micronutrient-rich foods cultivars through plant breeding, the process must not compromise factors such as tolerance to abiotic and biotic stress, crop productivity, and acceptable end-use quality. Biofortification is a viable option to complement vitamin and mineral deficiencies intervention strategies.

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