SCIENTIFIC PANEL
ON RESPONSIBLE PLANT NUTRITION

PLANT NUTRIENTS ARE ESSENTIAL FOR THE ALLEVIATION OF CHRONIC AND HIDDEN HUNGER

Issue Brief 05, October 2023

KEY POINTS

Most mineral nutrients, essential amino acids, vitamins and antioxidants, carbohydrates, proteins and fats to support human nutrition are obtained directly from plants or indirectly from animals which consume plants (Fig. 1). The nutrition of humankind therefore depends on providing nutrients to plants, so they grow optimally and produce foods of suitable nutritional quality to support human health and well-being.

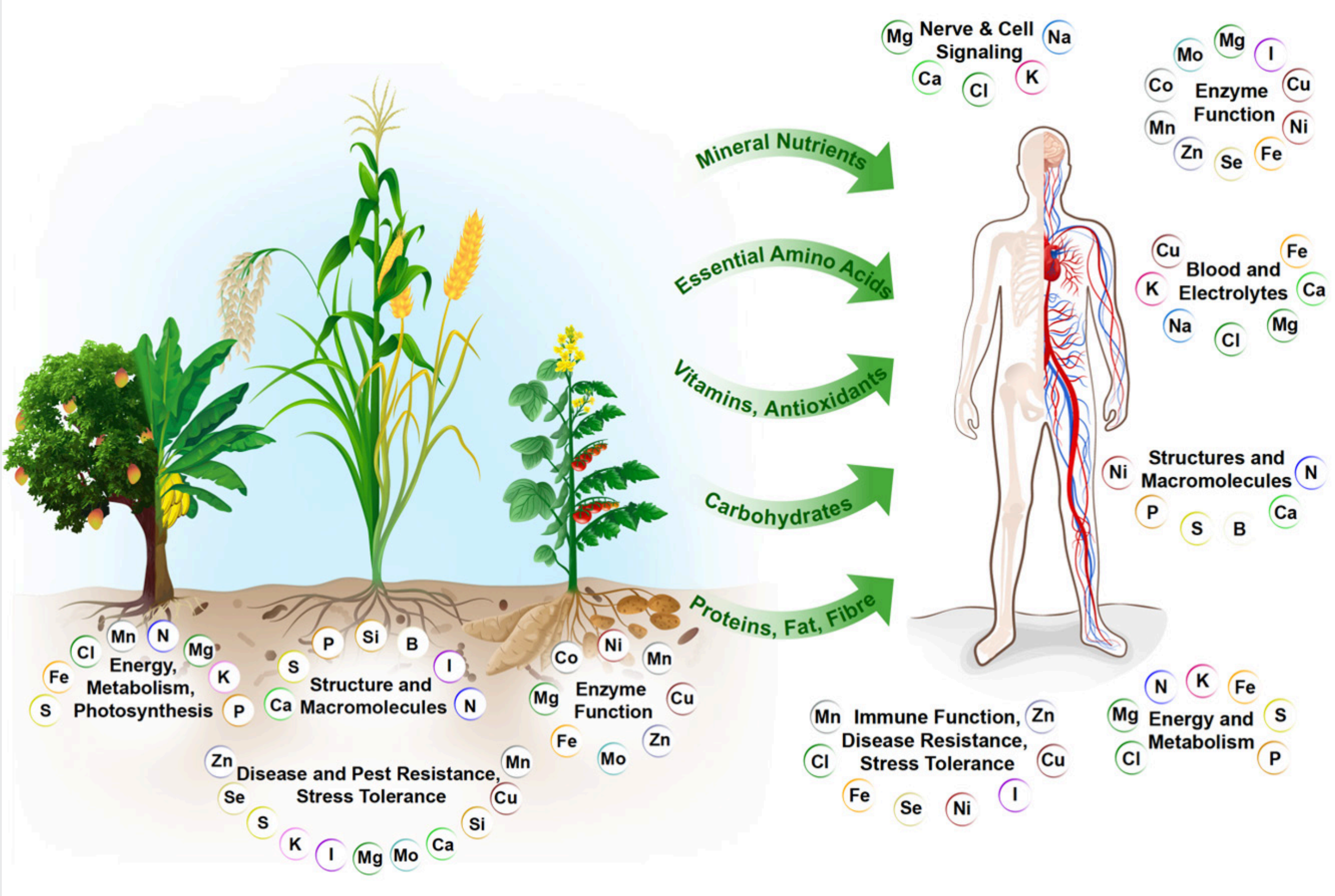

Figure 1. Nineteen mineral elements (plus C, H and O) are required for optimal plant growth and to support the nutritional quality of food products harvested for human consumption (1, 2).

The dual role that mineral elements play in plant and human health calls for a new paradigm in plant nutrition and fertilizer strategy. Cereals are the most important source of nutrition for most of the global population. Hence, improving cereal productivity and nutrient bioavailability through breeding and the supply of plant nutrients has great potential for alleviating hunger and malnutrition. Fruits, nuts, vegetables, oil crops, legumes, and roots & tubers provide dietary diversity, are excellent sources of nutrients. Their consumption often also enhances the bioavailability of cereal-derived nutrients.

INTRODUCTION

Nearly 10% of the world's population suffers from chronic hunger, the persistent inability to access enough food to eat. At the same time, 25% face 'hidden hunger' caused by a deficiency of mineral micronutrients or vitamins in their diets *(3, 4)*. Nutritious and healthy diets are out of reach for about three billion people *(4, 5)*. Despite huge efforts made in the past five decades, chronic and hidden hunger still persist and are even growing *(6, 7)*. One reason for this trend is the low nutrient status of a significant proportion of the world's agricultural soils. These soil nutrient deficiencies are the results of poor farming practices, the export of nutrients in harvested crop products, and unfavorable soil conditions. Thus, inadequate or unbalanced plant nutrition thus limits crop productivity and compromises the nutritional value and quality of the food produced *(8, 9)*.

Another reason why chronic and hidden hunger persist on a global level is lack of awareness. Food systems do not adequately focus on the health of the consumer, the production and distribution of food is inequitable, and much food is lost or wasted *(10)*. A lack of dietary diversity, high reliance on a few staple food crops and poor access to nutrient-dense plant and animal foods also affect human health in many countries. To alleviate human hunger requires cost-effective methods to provide local plant nutrient needs. Economic and regulatory policies need to facilitate markets and support the implementation of appropriate agronomic and educational practices to utilize plant nutrients efficiently and safely.

Based on these local and global challenges, there is the urgent need to **i)** increase awareness and knowledge of how plant nutrition and human nutrition are intertwined and **ii)** develop environmentally sound and economically sustainable practices to provide the mineral nutrients needed to support human health. Here, we describe how responsible plant nutrition can contribute to mitigating chronic and hidden hunger and achieving the second UN Sustainable Development Goal to **'end hunger, achieve food security and improved nutrition, and promote sustainable agriculture.'**

Responsible plant nutrition *(11)* aims to:

- **Improve income, productivity, nutrient efficiency, and resilience of farming.**
- **Enhance human health through nutrition-sensitive agriculture.**
- **Lift and sustain soil health.**
- **Increase nutrient recovery and recycling from waste.**
- **Minimize greenhouse gas emissions, nutrient pollution, and biodiversity loss.**

WHAT ARE THE ISSUES?

ISSUE 1: PLANT NUTRIENTS HAVE SAVED BILLIONS FROM STARVATION, BUT CHRONIC HUNGER REMAINS WIDESPREAD.

People suffer from chronic hunger when they are regularly unable to access enough food to eat. While undernourishment has been greatly reduced in recent decades through increased food production, the global share of undernourished people has risen from about 8% in 2019 to over 9% at present and is particularly large in sub-Saharan Africa (Fig. 2). The number of people affected by chronic hunger was between 691 and 783 million in 2022, with an increase of 122 million since the outbreak of the COVID-19 pandemic *(4)*. More than a quarter of a billion people are facing acute levels of hunger.

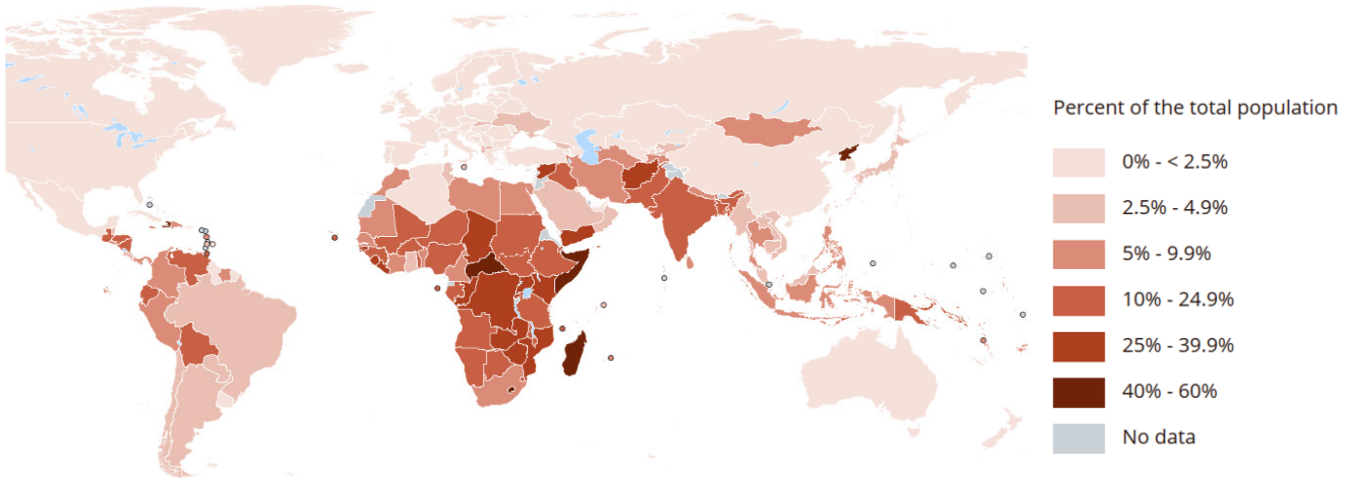

***Figure 2.** Prevalence of undernourishment. 2020-2022 average (4).*

The central role plant nutrition plays for human nutrition and economic development is illustrated by the close relationship between crop productivity gains and fertilizer use *(12)*. Mineral fertilizers, particularly nitrogen (N), potassium (K), and phosphorus (P), have increased crop yields throughout much of the world. While plant nutrients provided by mineral fertilizers now feed about half of the world's population *(13, 14)*, huge regional differences exist *(11)*.

Of particular concern is the situation in much of sub-Saharan Africa, where chronic hunger and malnutrition persist in large parts because access to and use of fertilizers is severely constrained *(15)*. Average fertilizer usage rates in east, central, and west Africa are mostly still below 20 kg

NPK/ha, although encouraging upward trends have occurred in recent years in Ethiopia, Kenya, Tanzania, Malawi, Zambia, Ghana, Nigeria, and Mali *(16)*. Across Africa, reliable data for regional nutrient use is available only for N, P, and K with little information on any of the remaining plant nutrients. What is known, however, is that micronutrient deficiencies in soils, crops, and humans are common in many African countries (*16–18)*.

Inadequate plant nutrient provision drives yield gaps, low productivity, and undernourishment *(19)*. Plant nutrient deficiencies are regarded as some of the most critical yield constraints in sub-Saharan Africa and other resource-poor regions *(20, 21)*. Calories, proteins, and nutrients are exported from cropland soils and pastures as plant products to feed humans and animals. Yet, when exported nutrients are not replaced or maintained, crop and pasture productivity and thus food quality inevitably decline. As such, widespread negative nutrient balances--especially for N, P, and K--in which nutrient exports exceed nutrient inputs, have been known for over 30 years in sub-Saharan Africa *(22, 23)*. More recent analysis of on-farm nitrogen balances across 52 African countries demonstrated that little progress has been made *(24)*. The ultimate impact of a persistent negative nutrient balance on productivity varies with environment but is most critical in marginal agricultural lands with low natural fertility and few resources to replenish exported nutrients with inorganic or organic fertilizers.

The 2021 food crisis in Sri Lanka is a stark reminder of how responsible plant nutrition underpins food security. In May 2021, the government of Sri Lanka banned the import of inorganic fertilizers and agrochemicals with the aim to turn the Sri Lankan agriculture strictly organic. The availability of organic fertilizers nationally was, however, inadequate and failed to replace nutrients no longer supplied by mineral fertilizers. Immediately, yields of staple food crops such as rice, maize, and vegetables declined by 20-60%. Although the fertilizer ban was lifted in November 2021 and fertilizer use gradually increased towards pre-ban levels, 2023 cereal production is forecast to still be 14% lower than the last previous five-year average *(25)*. These unintended declines in Sri Lankan crop production due to the lack of nutrient inputs stress – yet again – that food production relies heavily on the balanced input of plant nutrients, irrespective of the type of fertilizer applied.

ISSUE 2: HIDDEN HUNGER DUE TO THE INSUFFICIENT SUPPLY OF MINERAL MICRONUTRIENTS AND VITAMINS IN FOODS IS A GLOBAL ISSUE.

Hidden hunger refers to the dietary deficiency of vitamins or mineral micronutrients which are essential for human health, including physical development, brain, thyroid, and immune system functions (Fig.1). In many cases, hidden hunger occurs as the result of consuming an energy-dense, but nutrient-poor diet *(26)*. Such diets lead to the intake of sufficient amounts of energy in the form of calories, but not of the required nutrients. More than 2 billion people globally are affected by various forms of hidden hunger, particularly in low- and middle-income countries where diets lack diversity, and choices are limited due to poverty *(27)*. Hidden hunger is most prevalent on the African continent and in South Asia, with children and women of reproductive age the most vulnerable *(7, 28)*.

Seven mineral nutrients--iron (Fe), zinc (Zn), copper(Cu), calcium (Ca), magnesium (Mg), selenium (Se), and iodine(I)--and several vitamins are often lacking in human diets. The most common deficiencies are due to the lack of Fe, Zn, vitamin A, and vitamin B9 (folate) *(29)*, which, alone or in combination, affect 30-90% of all pre-school or non-pregnant females globally (Fig. 3). In total, half of preschool-aged children and two-thirds of non-pregnant women of reproductive age worldwide have micronutrient deficiencies of Fe, Zn, or I *(7)*. Widespread occurrence of Zn deficiency in human populations, especially in South and Southeast Asia, is also associated with a high incidence and severity of childhood infectious diseases *(28)*.

The global challenge of hidden hunger is staggering but is not restricted solely to developing countries. Micronutrient deficiencies are also a major problem in high income countries with 50% and 33% of UK and US women, respectively, suffering from at least one micronutrient deficiency *(7)*. Low dietary intake of several micronutrients, especially Fe, Zn, and I, is increasingly reported for European populations *(30, 31)*. Common diets consumed by elderly people in Europe are low in micronutrients, while high alcohol consumption interferes with intestinal absorption of micronutrients, thus aggravating micronutrient deficiencies. Vegans and vegetarians are also at a high risk of reduced mineral nutrient intake *(31)*.

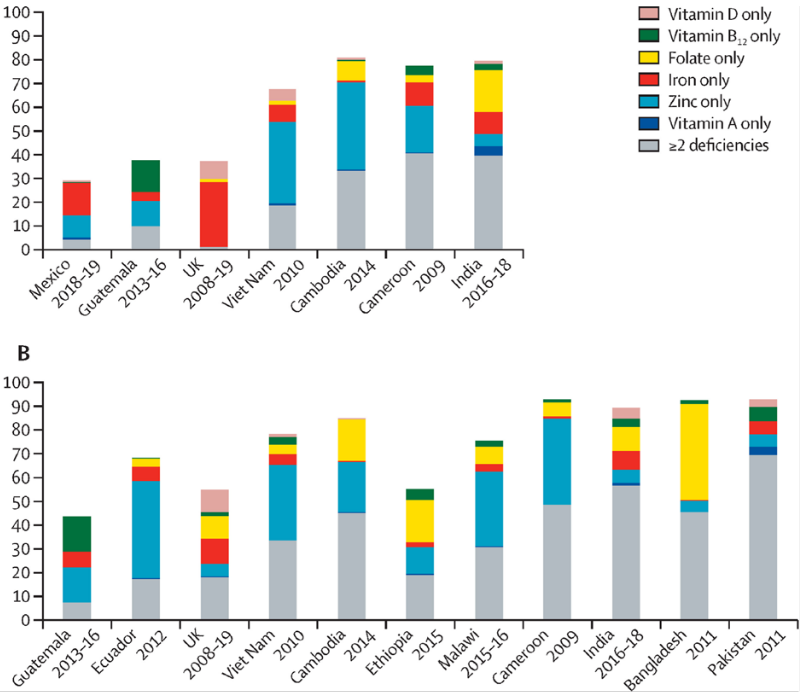

Figure 3. *Prevalence of two or more micronutrient deficiencies in % in A) school age children 5-59 months and B) non-pregnant women aged 15-49 years (7)*

Globally, the risk of developing Zn and vitamin A deficiencies has decreased over the last three decades, whereas the risk of developing Fe deficiency has remained at a relatively high level (Fig. 4). In India and Turkey, the decrease in prevalence of Zn deficiency is at least partially attributable to increased Zn fertilization interventions *(32, 33)*.

Another essential micronutrient that is at times not provided at adequate levels with diet is selenium (Se), which has important roles in thyroid function, cognitive development and as an anti-inflammatory component *(35, 36)*. Up to 0.5 – 1 billion people globally may have insufficient intake

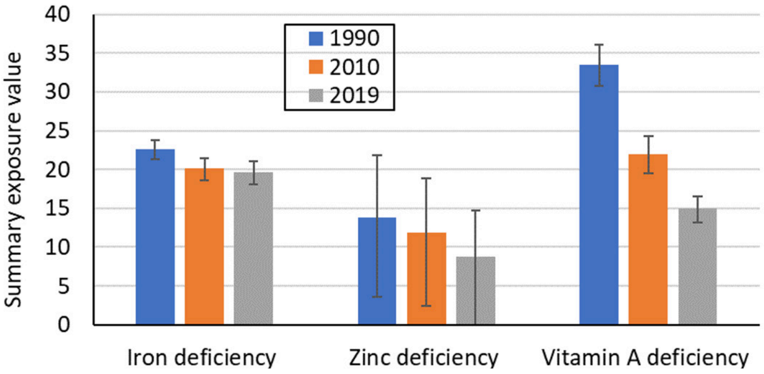

Figure 4. *Global age-standardized summary exposure values (SEV) to deficiency of iron, zinc, and vitamin A in 1990, 2010, and 2019. Error bars represent 95% confidence intervals. SEV = 100 when the entire population is at maximum risk and is zero when the entire population is at minimum risk (34).*

of Se, including populations in western and northern Europe, eastern and central Siberia, New Zealand, and in parts of China *(37, 38)*. Severe Se deficiency causes endemic human diseases such as Keshan disease (a cardiomyopathy) and Kaschin–Beck disease (an osteoarthropathy). While Keshan disease has been eliminated by supplementing with Se tablets, Kaschin–Beck disease still occurs in some areas of the Sichuan-Tibet region of China and in southeast Siberia (39). Human Se deficiency has also been reported for a number of countries in Africa *(40–42)*. Deficiency of Se due to inadequate dietary intake is driven by low concentrations of plant-available Se in some agricultural soils. Hurst et al *(42)* reported a very strong link between soil Se availability and daily dietary Se intake. The lowest daily dietary Se intake was found in villages where soils were acidic, while the highest daily dietary Se intake was taking place in villages with high pH soils. Chemical availability and root uptake of Se is extremely low in acidic soils while it is very high in high pH soils.

Dietary deficiency of I is also highly prevalent, despite worldwide usage of iodized salt. Iodine deficiency primarily affects thyroid and brain function, and mental development *(43)*. Around 2 billion people are estimated to be at risk of I deficiency, especially in western countries *(44, 45)*. There is also increasing evidence for a nutritional role of I in plants *(46)*.

ISSUE 3: LOW NUTRIENT LEVELS IN CROPS AND THE LACK OF DIVERSITY IN FOOD SYSTEMS ARE PRIMARY CAUSES OF HIDDEN HUNGER.

Plants are major dietary sources of macro- and micronutrients that humans require. As Figure 5 illustrates, plant-based foods provide about 80% of calories, 56% of proteins, 50 – 95% of vitamins, and 40 – 85% of minerals to the global population *(47)*. The remaining human nutritional needs are provided by animal products, which in turn depend on plant production. However, the values in Figure 5 mask large variations among and within countries. The relative contributions of plant-based foods are highest in low-income countries where consumption of meat, fish, eggs, and dairy products is low. Animal-based foods have higher bioavailability of Fe and Zn; thus, in regions where animal-based foods are consumed, the relative contributions of plant-based foods to bioavailable Fe and Zn are considerably smaller than those shown in Figure 5. To the contrary, in regions with little to no consumption of animal-based foods, a large percentage of Fe and Zn is provided by cereals with low nutrient density and bioavailability. Such a plant-based diet barely provides all critical nutrients to meet basic human needs.

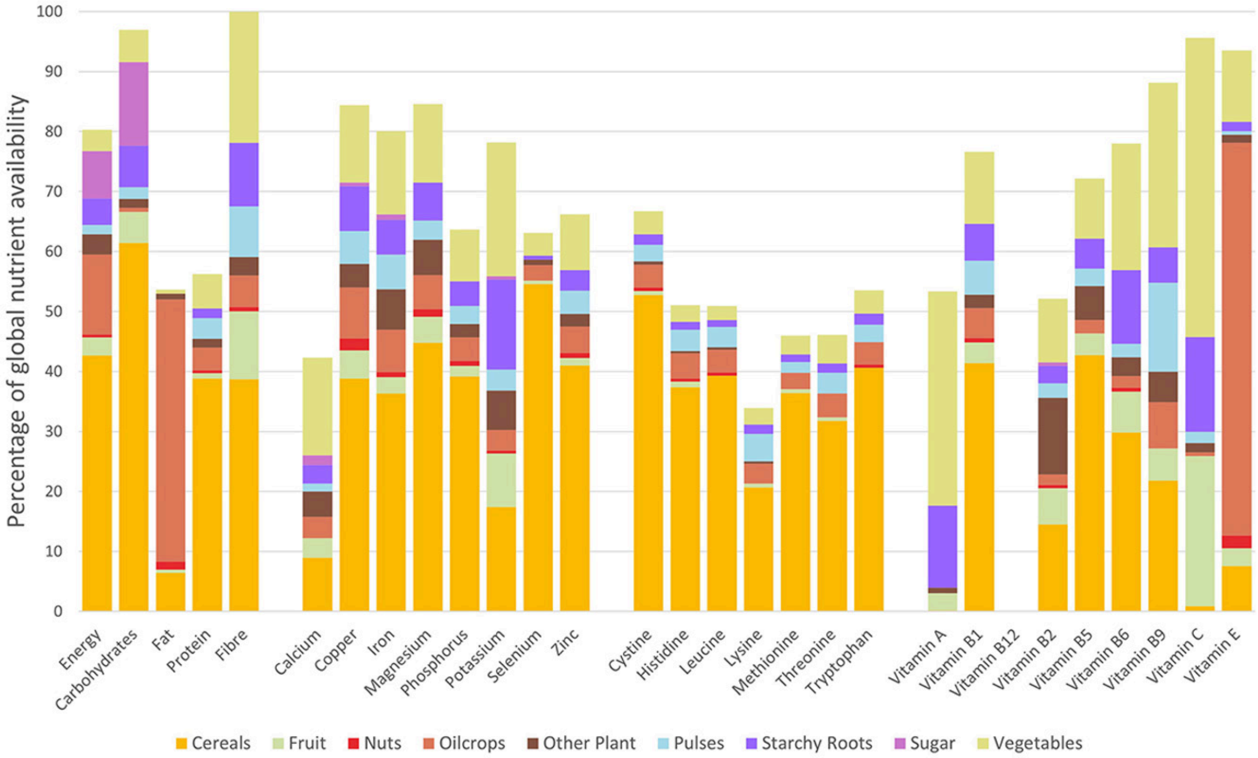

Figure 5. *Contribution of plant foods to dietary energy, carbohydrate, fat, protein, fiber, mineral nutrient, amino acid, and vitamins. These values were calculated using the DELTA Model® and adjusted for waste and inedible portions. Bioavailability/digestibility were corrected for proteins and amino acids but not for other categories. Where bars do not represent 100% of the dietary provision, the remainder is predominantly provided by food sources produced from animals (47).*

Plants with low nutrient contents result in foods of low nutritional value and limited diversity of diet – the main causes of hidden hunger. Cereals and tubers are staple foods for most populations in low-income countries. These crops, however, have relatively low concentrations of Fe, Zn (Table 1), and vitamins. Additionally, some cereals, like rice and wheat, are polished or milled into white rice or white flour before consumption, further decreasing the concentrations of mineral nutrients (Table 1). Iron and Zn from plant-based foods are generally also less bioavailable for human absorption than Fe and Zn from animal-based foods *(48)*. Hence, a diet based only on cereals, roots, and tubers cannot provide sufficient levels of Fe, Zn, and vitamins. Instead, including vegetables, fruits, legumes, and some animal products increases nutrient intake to meet human requirements *(9)*. Fruits and vegetables are not only richer sources of vitamins and minerals than cereals and tubers; they also contain ascorbic acid (vitamin C) that enhances Fe absorption in the human gut.

Not many diets meet the recommendations for healthy nutrient intake. Globally, consumption of vegetables, fruits, and legumes is 40%, 60%, and 74%, respectively, lower than recommended *(3)*. For many reasons, a handful of staple crops of low nutrient density, including maize, wheat, and rice, dominate the global food and feed chains. These primary staple crops have also displaced nutrient-dense traditional food crops in previously more diverse farming systems. Owing to the great success of the Green Revolution, the production of staple cereal crops has more than doubled since the mid-1960s, while the production of pulse crops has lagged behind. As a result, the relative price of staple cereals has decreased, while that of pulses, animal meat, and fish has increased *(9)*. These changes have forced people with low income to rely more on staple foods at the expense of high-nutrient-density pulses and animal products.

		Fe (mg kg^{-1})	Zn (mg kg^{-1})
RICE	Brown rice	5 - 15	15 - 25
	Polished rice	3 - 10	5 - 15
WHEAT	Whole grain	20 - 35	15 - 35
	White flour	5 - 15	4 - 10
MAIZE		20 - 30	15 - 30
PEARL MILLET		30 - 60	25 - 50
BEAN		30 - 70	20 - 50
PEAS	Dried	30 - 70	30 - 60
LENTIL		40 - 70	30 - 50
CASSAVA ROOT		5 - 10	4 - 10
SWEET POTATO		5 - 15	5 - 10
IRISH POTATO		3 - 5	3 - 5

Table 1. *Common ranges of iron and zinc concentrations in cereals, tubers, and legume seeds.*

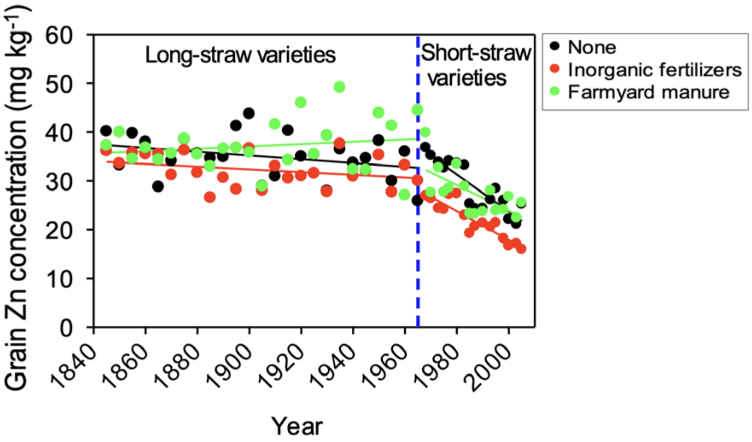

Figure 6. *Decreasing zinc concentration in wheat grain since the introduction of high-yielding semi-dwarf wheat varieties in the Rothamsted Broadbalk long-term experiment. Other mineral nutrients (Fe, Cu, Mn, and Mg) show similar decreasing trends (49).*

Crop breeding has successfully improved the yields of major cereal crops around the world. Yet, mineral nutrient concentrations of these cereal crops has declined due to higher yields resulting in nutrient dilution, narrower crop genetics, and/or soil nutrient depletion (49, 50). A long-term experiment at Rothamsted showed that the concentrations of Zn, Fe, Cu, and Mn in wheat grain have decreased by 30 – 50% since introducing semi-dwarf high-yielding cultivars in the mid-1960s (Fig. 6). This effect occurred even though the levels of these micronutrients in the soil remained stable. At the global scale, the benefits of increased yield to supply more food for expanding populations have so far mostly counterbalanced such nutrient dilution effects (51). However, there is an increasing risk that decreased concentrations of micronutrients in cereal grains will lead to lower dietary intakes of these nutrients if the dietary patterns remain unchanged.

Climate change is likely to worsen the micronutrient deficiency problem because increasing concentration of atmospheric CO$_2$ has a negative effect on nutrient concentrations in major food crops *(52–54)*. Field studies showed that the contents of protein, Fe, and Zn in the seeds of crops such as wheat, rice, peas, and soybeans decreased by 5 – 10% under elevated CO$_2$. Other crops, like maize and sorghum, were less affected *(52, 53)*. The reasons for these observations are not entirely clear but may include factors such as nutrient dilution due to increased yield, reduced transpiration limiting mass flow and nutrient translocation, disturbed nutrient uptake and assimilation, and/or changes in nutrient availability in the rhizosphere *(53, 55)*. Elevated CO$_2$ atmospheric concentrations could cause an additional 175 million people to become Zn-deficient and an additional 122 million people to become protein-deficient within the next 50 years *(54)*. For 1.4 billion women of childbearing age and children under five living in countries with >20% anemia prevalence, climate change could further reduce the availability of dietary Fe.

Jones et al. *(38)* predicted that changes in climate and soil organic matter content may lead to decreasing soil Se concentrations in agricultural areas, which could increase the prevalence of Se deficiency in humans. The combination of elevated atmospheric CO$_2$ concentrations and drought and heat stress can further limit soil mobility and root uptake of mineral nutrients, leading to decreased nutrient concentrations in edible parts of food crops. Lastly, soil moisture directly affects the diffusion of mineral nutrients towards root surfaces for their uptake into the plant, especially for less soluble nutrients such as Zn and Fe *(56)*. It is therefore not surprising that Zn deficiency due to low concentrations in cereal crops is more prevalent in low rainfall regions *(32)*.

SOLUTIONS AND NEEDED ACTIONS

Introducing more nutritious and healthier diets requires a profound food system transformation based on a continuous learning experience *(57)*. For example, diets proposed by the landmark EAT–Lancet Commission *(10)* may entail dietary gaps of minerals such as Ca, Fe, and Zn unless modified to include more foods from animal sources and from specific plant-based interventions *(58)*. Here, we outline key solutions for improving dietary mineral supplies. We focus on strategies that are accessible through primary crop production, the main entry point of mineral nutrients into the global food system.

1. RAISE AWARENESS OF THE CRITICAL ROLE OF RESPONSIBLE PLANT NUTRITION IN ALLEVIATING CHRONIC AND HIDDEN HUNGER

The close relationship between plant and human nutrition (Fig. 1) is still underappreciated and often subsumed by public opinions and policy decisions. Emphasizing the negative consequences of over-fertilization occurring in parts of the world often ignores the huge negative impact of poor plant nutrition on billions of people, particularly in low-income countries.

Responsibly replenishing nutrients removed in harvested products or lost due to soil degradation is essential if we are to increase productivity and food quality, and hence reduce human hunger. Responsible plant nutrition is a prerequisite to achieve the goals of sustainable intensification, regenerative agriculture, human nutrition and health, and protection of ecosystems. None of these critical initiatives can succeed without first addressing the need to provide adequate nutrients to support plant growth, crop yield, and crop quality *(15, 59–61)*.

Two discrete challenges related to fertilizer use must be solved in the coming decades *(11, 59, 62, 63)*: In regions in which fertilizer use is high (*e.g.*, North America, Europe, South and East Asia, parts of other regions), the challenge is to reduce excessive nutrient surpluses and losses from fertilizers and other sources, while maintaining or increasing crop yield and crop quality. In other regions, the challenge is to overcome insufficient nutrient availability that causes low crop productivity and poor nutritional quality, negative nutrient balances, and soil degradation which are also primary causes of chronic and hidden human hunger. Under these conditions, the potential for environmental damage from increased fertilizer use is minimal while the societal benefits would be huge.

Recognizing and emphasizing these two challenges for plant nutrient use is essential. Every country should develop a national nutrient roadmap that considers its specific needs, sets clear targets for nutrient use from different sources, including fertilizer, and provides a scientifically sound basis for advancing responsible nutrient use through associated technologies, policies, and investments.

Nutrient roadmaps must also include the specific contributions plant nutrition can make toward addressing hidden hunger issues. The use of plant nutrients and fertilizers in agriculture has also been constrained by the historically narrow definition of plant nutrients *(64)* that does not consider human nutritional goals. A new definition of a plant nutrient has been developed that states ***"A mineral plant nutrient is an element which is needed for plant growth and development or for the quality attributes of the harvested product"*** *(1)*. This broadens the number of elements considered plant nutrients, including some that are of crucial importance for human nutrition (*e.g.*, Se, I). Countries should adopt this new definition in their fertilizer regulatory systems, which would allow more critical mineral elements to be provided through fertilizers.

2. IMPROVE TARGETING OF CROP-SPECIFIC NUTRIENT DELIVERY

Designing lasting solutions to overcome chronic and hidden hunger through crop-based interventions requires sound targeting, i.e., knowing the specific soil conditions, crop requirements and human requirements. Many soils lack specific nutrients, thus playing a central role in chronic and hidden hunger. Particularly in regions with poor diets and low nutrient inputs, nutrient deficient soils directly impact plant nutrition and human nutrition. For example, in sub-Saharan Africa, statistically significant relations were found between soil nutrients and child mortality, stunting, wasting, and underweight *(65)*. Hence, any successful solution must start with knowledge of the local soil conditions. To achieve this, soil and plant testing has been a mainstay of fertilizer recommendations. Soil and plant testing are however, frequently too expensive, widely unavailable, and difficult to interpret – thus impractical at the very small scale and remote locations of many of the neediest agricultural producers.

In the absence of hyper-local soil and plant testing, alternative strategies to recommend and target plant nutrient supplies are needed. At a regional scale, the impracticality of traditional soil and plant testing strategies can be partially addressed by developing robust, practical decision support frameworks. Building on digital technologies, novel analytical technologies, modeling, and artificial intelligence can help mapping, predicting, and targeting plant and human nutrient deficiencies. Inexpensive and simple spectroscopy for soil analysis, for example, has allowed the assessment of soil conditions over a much broader scale and to a greater resolution than could have been achieved by laboratory soil analysis *(66)*. Good progress has also been made to create a global soil spectral calibration library and estimation service *(67)*. The 30-m resolution digital soil map developed for Africa *(68)* is an excellent example for an integrated use of novel digital technologies. It provides a sound entry point for agronomic and plant nutrition targeting and advisory applications, such as the Virtual Agronomist being developed by iSDA (Innovation Solutions for Decision Agriculture). Information on plant nutrient availability at a local scale can also be derived by mapping grain nutrient content along with soil properties, and environmental and agronomic covariates *(69)*.

This and other information can guide the development of regional or locally tailored fertilizer blends, including micronutrients, that meet crop productivity as well as human nutrition requirements. The crop and human nutrition impact of these products must be evaluated carefully, and quality control systems must be developed to ensure that the product the end user is receiving contains the nutrients in the amounts and purity levels they purchased.

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1. https://www.isda-africa.com/virtual-agronomist/

3. DEVELOP SUSTAINABLE STRATEGIES FOR NUTRIENT DELIVERY THROUGH AGRO-BIOFORTIFICATION

In regions with soil nutrient deficiencies, fertilizers represent a sustainable strategy. By applying micronutrients with fertilizers, farmers can boost crop yields, their incomes, the micronutrient content in crop products, and, ultimately, human health. Agronomic biofortification is both a means to optimize crop productivity and economic profit and to provide nutrient-dense food to a larger population, especially crucial among rural resource-poor settings *(70)*. The feasibility of agronomic biofortification in combatting hidden hunger depends on factors such as fertilizer access, crop type, crop genotype, agronomic practices, climate, and soil *(70)*. Many studies have demonstrated the positive impact of fertilizer-based biofortification with Se, Zn, or I on the grain content of these elements, primarily in staple cereal crops. Turkey, Pakistan, India, and Finland are illustrative examples of successful agronomic biofortification programs.

In the 1990s, Zn deficiencies in soils and cereal grains were found to be closely related to human Zn deficiency in Turkey *(71)*. Since then, Zn fertilization increased both cereal grain production and grain Zn concentrations *(72).* In some locations in Central Anatolia, the soil Zn content was so low that wheat plants responded to Zn fertilization with spectacular 5-fold increases in grain yield and 2-fold increases in grain Zn levels. Following these findings, use of Zn-containing NP and NPK fertilizers in Turkey increased from zero in 1993 to over 600,000 tons in 2020 (Toros Agri; unpublished results), improving both farmers' profits and human Zn nutrition.

Similarly, in the Punjab and Sindh provinces of Pakistan, Zn fertilization increased wheat yield by an average of 8% and 14%, was highly profitable for farmers, and increased dietary Zn supply by 16% and almost halved the prevalence of Zn deficiencies in the populations of these two states *(73)*. In India, the government started investing in increasing Zn contents of crops because the costs of biofortification strategies were found to be lower than the human and economic costs associated with hidden hunger *(74)*. The Indian government as well as state governments subsidized fertilizers to contain Zn to encourage their applications. For example, in 2015 the Andhra Pradesh government initiated a program that provided a 50% subsidy for micronutrients. Soil data were used to identify areas critically deficient in micronutrients and farmers in deficient areas could buy zinc, gypsum, and boron from state agricultural department outlets at reduced rates. In 2017–18, the subsidy was raised to make micronutrients freely available to eligible farmers *(33)*. Overall, use of $ZnSO_4$ as a fertilizer in all India increased by 65% from 2004/2005 to 2020/2021.

The Finnish Se biofortification program provides an excellent example of the efficacy of agronomic biofortification and the importance of ongoing monitoring to fine-tune such interventions *(75)*. In 1984, the incorporation of Se into granular fertilizers became mandatory, with the amount of added Se initially set at 16 mg/kg fertilizer (1984-1990). Thanks to this regulation, dietary Se intake quadrupled while the plasma/serum Se concentrations of adults doubled (Fig. 7). The subsequent adjustments in fortification to 6 mg/kg fertilizer (1990-1998), 10 mg/kg fertilizer (1998-2007) and 15 mg/kg fertilizer (since 2007) stabilized the plasma/serum Se concentrations of Finnish adults at an optimal level (Fig. 7). Noticeably, besides enriching Se in wheat grain for direct human consumption, the country-wide biofortification strategy also increased the Se contents in animal feed, which benefitted animal health and raised Se contents of milk and meat for human consumption *(76)*.

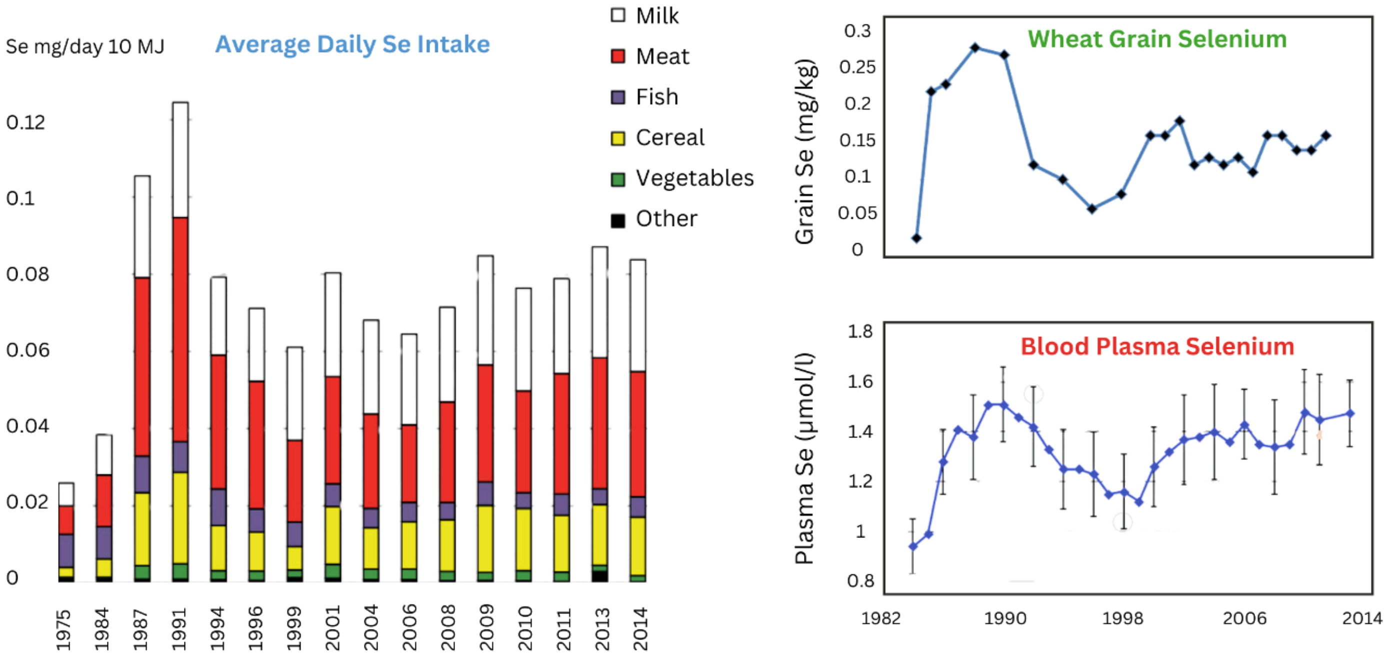

Figure 7. Enrichment of fertilizers with selenium has improved Se nutrition of humans in Finland. Left: Average selenium intake of Finnish population from different dietary sources in response to agro-biofortification of Se in compound fertilizers. Right: Change in wheat grain and plasma serum Se following fortification of fertilizers with Se. Re-drawn from Alfthan et al. (75) and Eurola et al. (76).

Enrichment of staple food crops with Se through fertilizers has also been demonstrated in other countries and food crops, including soybean in Brazil *(77)* or maize in Malawi *(78, 79)*. Foliar spray of Se, for example in the form of Na-selenate, was highly effective in increasing Se concentrations in wheat and rice *(80, 81)*. Since Se has a key role in antioxidative defense mechanisms, Se-biofortified crops may also exhibit better tolerance to environmental stress conditions *(82)*.

Recent studies demonstrate that foliar spray of I fertilizers may also result in impressive increases in I concentrations of wheat and rice *(80, 83)*, apples *(84)*, vegetables, and other crops *(40, 85)*. By co-fertilizing I together with Zn and Se, multiple deficiencies can even be addressed in an effective manner.

New technologies such as nano-fertilizer may offer huge potential for the targeted delivery of critical mineral elements to crops, particularly also micronutrients of importance to hidden hunger, such as Zn or Fe *(86, 87)*. Nanoparticles carrying such nutrients can translocate from exposed leaves to unexposed tissue, which may enable designing more efficient foliar fertilization products for nutrients that are less mobile in soil or plant *(86)*. However, any such novel solutions must be evaluated thoroughly with regard to understanding the underlying mechanisms, actual crop nutrition performance in the field, and potential environmental risks.

The main challenge for agronomic biofortification solutions is the ability to scale them quickly in regions where they are most needed and can be most effective. Where fertilizer fortification benefits both crop yield and human nutrition, adoption may be mainly driven by farm-level economics, agri-business, access to the right fertilizer, and good agronomic advisory. However, where fertilizer fortification mainly improves human nutrition without clearly enhancing crop productivity or a price premium for producing enriched foods, there is less incentive for a grower to invest in this practice. Under these circumstances, government policies or non-governmental support are required to cover the costs of such interventions to assure essential micronutrients to be delivered to those in need.

While government or NGO support may initially be required in circumstances where market forces are insufficient, the sustained distribution of subsidized micronutrient fertilizer may be fiscally challenging for governments, and it may also crowd out commercial investment. There is need to develop market-driven solutions that integrate micronutrients of human importance into sustainable food production standards. This will also require embedding human nutrition into public and private agricultural advisory and extension *(88)*.

4. DIVERSIFY CROPPING SYSTEMS AND GENETICALLY ENRICH CROP VARIETIES

Diets that include pulses, vegetables, and fruits, in addition to staple crops, provide more micronutrients and vitamins than those based largely on cereal crops. Broadening the diversity of cropping systems by growing more nutritious crops is generally desirable but requires suitable environmental conditions and markets *(89)*. Where possible, more attention should be paid to improving and growing neglected or underutilized crops. Many of these are rich in nutrients or may serve as important genetic sources for improving the nutritional diversity of staple crops grown in more favorable locations *(90, 91)*. For example, millets and nutrient-rich crops, such as quinoa, chia, or teff contain richer dietary fibre sources, and higher protein quality with more enriched essential amino acids compared to modern varieties of rice and wheat *(90)*. The low productivity of these species, however, limits their potential impact. Even if these nutrient-rich crops were to be used more widely, efficient strategies are still needed to nutritionally enhance the world's staple food crops and replace plant nutrients exported in the harvested crop *(92)*.

Huge impacts on global nutrition could be made with greater investment to increase the nutrient value of staple cereals and roots & tubers since these two crop categories account for a large share of human nutrition (Fig. 5). However, to reap the potential benefits from genetic improvement, both agronomic and genetic biofortification approaches should be integrated. For example, soil or foliar applications of Zn are necessary in Zn-deficient soils to realize the biofortification potential of high-Zn crop varieties *(93)*. Likewise, because the concentrations of Fe and Zn in cereal grain correlate with the content of protein, increasing the dose of N fertilizer within a certain range often also leads to increased concentrations of Fe and Zn in the grain *(94)*.

Genetic biofortification has been used successfully to raise the content of Fe and Zn in cereal and legume grain. The HarvestPlus program has, for example, succeeded in conventionally breeding "Iron bean" and "Iron pearl millet" varieties with 60 – 90% higher Fe concentrations in the seeds compared to non-biofortified varieties. When eaten regularly, they can provide up to 80% of daily Fe needs and significantly improve the Fe status and cognitive performance in women and school-going adolescents, as demonstrated in Rwanda and India *(95, 96)*. Similarly, varieties of Zn-biofortified wheat, rice, and maize, and provitamin A-biofortified cassava, maize, and orange sweet potato have been bred and released in many countries. Approximately 8.5 million farm households in 40 countries across Africa, Asia, and Latin America are growing these biofortified crops. It has been estimated that these biofortified crops can provide an extra 25%, 35%, and >85% of the estimated average requirement of Zn, Fe, and provitamin A, respectively *(29)*.

Where conventional breeding cannot achieve the biofortification targets due to the absence of a suitable target metabolic pathway or limited natural genetic variation, genetic engineering can be used to augment micronutrient content of the crop. An excellent example is Golden Rice, which has been engineered to contain several genes for the biosynthesis of β-carotene (provitamin A) in the rice endosperm that otherwise lacks this ability *(97)*. Substituting Golden Rice for conventional rice could provide 89-113% and 57-99% of the recommended vitamin A requirement for preschool children in Bangladesh and the Philippines, respectively *(98)*. Golden rice has performed well in the field *(99)*, and has in terms of yield, and has recently been approved for cultivation in the Philippines. Thanks to transgenic approaches, staple food crops could

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2. https://www.harvestplus.org/home/crops/

be successfully biofortified utilizing transgenic approaches to enhance the uptake, translocation, storage, and bioavailability of Fe and Zn *(29, 100, 101)*. Transgenic approaches may also enable a better understanding of the underlying biological processes, which could then help exploit natural sources of genetic variations through conventional breeding *(102)*.

Gene editing is another powerful technology that can be used to enrich crops with micronutrients and vitamins *(103)*. For example, most foods contain little amounts of vitamin D since plants are very poor sources of this essential vitamin. Gene editing allowed modification of a single gene in tomatoes to produce more provitamin D, which humans can then convert to vitamin D *(104)*. By combining gene editing, genetic engineering, and conventional breeding, it should become possible to enrich multiple micronutrients and vitamins within the same crop, making staple crops more complete sources of nutrition than they are at present. Such technological innovations are considered to be highly cost-effective for tackling hidden hunger, but they will require wider acceptance by society *(29)*.

Biofortification, whether through breeding, fertilization, or molecular techniques is not however, a silver bullet solution to the world's hidden hunger problems. It can only succeed if there is no yield or income penalty, and if it is embedded into more holistic strategies for improving diets and nutrition *(105)*. To motivate and encourage farmers to improve the nutrient density in crops while maintaining high yield, incentive-based solutions and policies should be implemented. New metrics such as “grain nutrient yield” could be considered and adapted in global and local crop trade and markets *(106)* as an efficient innovation to address hidden hunger problems.

WHO NEEDS TO DO WHAT?

Educators, journalists, communicators, and influencers: raise awareness of the importance of plant nutrition for human nutrition, the world-wide problems of chronic and hidden hunger and the need to safely and effectively provide plant nutrients to support plant productivity and food quality for human health.

Policy makers: monitor and assess the nutritional status of the population, implement cost-effective strategies to address chronic and hidden hungers and facilitate the development of a sustainable fertilizer policy. Change fertilizer regulations to include all nutrients that are important for crop and human nutrition.

Fertilizer industry: develop, produce, and distribute cost-effective fertilizer products to enhance productivity and address chronic and hidden hunger.

Farmers, extensionists, farm advisers, and service providers: educate and train growers on the need for and benefit of plant nutrients to enhance crop productivity and food quality. Develop mechanisms to sustainably provide plant nutrients without causing environmental harm. Adapt technologies to improve crop productivity and nutrition, reduce nutrient losses, and improve profitability. Incorporate human nutrition into agricultural extension and advisory systems (88).

Consumers: diversify diets for better and more balanced nutrition and reduce food waste. Demand more nutrient-enriched food.

Food industry: create more demand for nutrient-enriched food and rewards farmers for producing it.

Investors: invest in developing nutrition-sensitive fertilizer markets through innovative marketing and distribution chains, development of innovative systems of information delivery, and provision of credit and insurance systems.

Scientists: develop more cost-effective and scalable methods to assess the nutrient status of plants and soil. Develop and extend sound nutrient management practices that improve nutrient use efficiency. Produce crop varieties that yield harvests enriched with micronutrients and vitamins.

Civil society organizations: recognize the key role plant nutrients play in human nutrition outcomes. Support the appropriate and environmentally sound development and distribution of plant nutrient products. Educate the population on the critical role of plant nutrition in alleviating chronic and hidden hunger. Embrace modern, science-based genetic improvement technologies, including genetic engineering and gene editing.

WHAT WOULD SUCCESS LOOK LIKE?

Chronic hunger is reduced significantly by increasing crop productivity through increased availability and optimized use of plant nutrients, especially in Africa.

Hidden hunger is alleviated through agronomic methods and biofortification of micronutrients, diversification of diets that include more nutrient-dense crops, and development of crop varieties enriched with vitamins and micronutrients.

Greater societal recognition of the key role of plant nutrition to reduce hunger, malnutrition and improve human health outcomes globally.

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