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Review

Research agenda for holistically assessing agricultural strategies for human micronutrient deficiencies in east and southern Africa

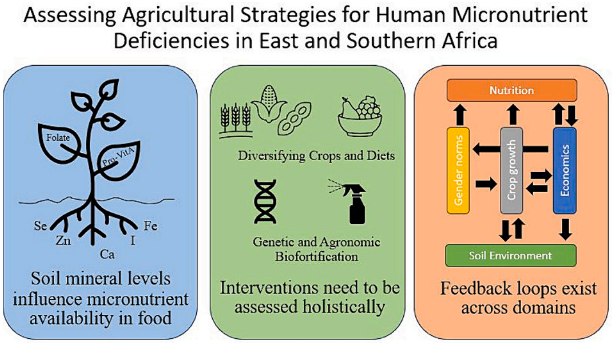
Philip Grabowski [a,*], Douglas Slater [b], Wanjiku Gichohi-Wainaina [c,d], Job Kihara [e], Regis Chikowo [f], Agnes Mwangwela [g], Dalitso Chimwala [g], Mateete Bekunda [h]

[a] Taylor University, Department of Biology, Environmental Science and Sustainable Development, Upland, IN, USA
[b] Michigan State University, Department of Community Sustainability, East Lansing, MI, USA
[c] International Crops Research Institute for the Semi-Arid Tropics, Lilongwe, Malawi
[d] WorldFish Center, Penang, Malaysia
[e] International Center for Tropical Agriculture, Nairobi, Kenya
[f] University of Zimbabwe, Harare, Zimbabwe/CIMMYT, Harare, Zimbabwe
[g] Lilongwe University of Agriculture and Natural Resources, Lilongwe, Malawi
[h] International Institute of Tropical Agriculture, Kampala, Uganda

HIGHLIGHTS

- Human micronutrient deficiencies in sub-Saharan Africa are connected through complex pathways to how soils are managed.
- We synthesize experiences from Malawi and Tanzania with literature on crop management for human micronutrient deficiencies.
- Addressing micronutrient deficiencies requires considering productivity, economic, environmental, social and human domains.
- Research on soil-nutrition linkages should consider the feedback loops across the 5 domains of sustainable intensification.
- Interdisciplinary and participatory research to effectively link soils to human health supports sustainable development.

GRAPHICAL ABSTRACT



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ABSTRACT

Context: Human micronutrient deficiencies in sub-Saharan Africa are connected through complex pathways to soils and how soils are managed. Interventions aiming directly at nutrient consumption, such as supplements and food fortification, have direct impacts but are often limited in their reach and require continuous support. In contrast, less direct changes, such as agricultural diversification and agronomic biofortification, are complicated by a wide array of factors that can limit progress toward nutritional outcomes. However, changes in agriculture

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* Corresponding author at: Department of Biology, Environmental Science and Sustainability, Taylor University, 1846 S Main St., Upland, IN 46989, USA.
E-mail address: philip_grabowski@taylor.edu (P. Grabowski).

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Nutrition
Biofortification

and dietary patterns, if successfully linked to deficiencies, provide a more systemic transformation with the potential to achieve wide-reaching and self-perpetuating attainment of nutritional goals.

Objective: The purpose of this paper is to advance theoretical frameworks and research methods for holistic analysis of agriculture-based interventions for micronutrient deficiencies.

Methods: We synthesize lessons from the literature and from the Africa RISING project in Malawi and Tanzania about the connections between soil nutrients and human micronutrient deficiencies from the perspective of the five domains of sustainable intensification (productivity, economic, environmental, human condition and social).

Results and conclusions: We present a menu of indicators for future research on the soil-plant-food-nutrition pathway related to micronutrient deficiency and smallholder farming that need to be considered to effectively assess how agricultural interventions may or may not result in the desired nutritional outcomes. Ultimately, addressing micronutrient deficiencies through agricultural interventions requires a holistic approach that considers all five domains. Research on soil-nutrition linkages should consider the feedback loops across the five domains of sustainable intensification.

Significance: Interdisciplinary and participatory research to effectively link soils to human health supports sustainable development.

1. Introduction

Nutrition problems in sub-Saharan Africa are connected through complex pathways from what is grown on-farm and how soils are managed to dietary intake. Although the Green Revolution encouraged the development of high-yielding staple crops to provide calories to vulnerable populations, it also resulted in decreased micronutrient content due to a dilution effect (Welch and Graham, 2004; Fan et al., 2008). Various programs and stakeholders seeking to address malnutrition have traced clinical micronutrient deficiencies upstream to farm management challenges and sought the help of agronomists to reduce childhood malnutrition (Bezner Kerr et al., 2007). More specifically, micronutrient deficiencies are described as the hidden hunger, with many important public health and economic challenges (de Valença et al., 2017). Inadequate iron, zinc, iodine, vitamin A and folate are some of the most widespread micronutrient deficiencies having important health impacts for a significant portion of the population (Bailey et al., 2015). Early research focused on the relationship between soil micronutrient content and human nutrition, such as Nube and Voortman (2006), established positive relationships between selenium and iodine levels in the soil and human nutrition outcomes, though an unclear relationship for iron, zinc, magnesium, and manganese. For zinc however, a global relationship has been shown where regions with human zinc deficiencies also have soil zinc deficiencies (Alloway, 2009).

The strategies for addressing micronutrient deficiencies can be organized by the locus of change across the soil-plant-food-nutrition pathway (Fig. 1). Strategies aiming to supply micronutrients at the end of the pathway, such as supplements and food fortification, can have a more direct impact on nutrition than efforts to supply micronutrients at the start of the pathway, such as genetic or agronomic biofortification. However, the interventions at the end of the pathway are less systemic, thus requiring continued intervention to address micronutrient deficiencies. Interventions at the start of the pathway are less direct, with a host of factors that complicate progress toward nutritional outcomes,

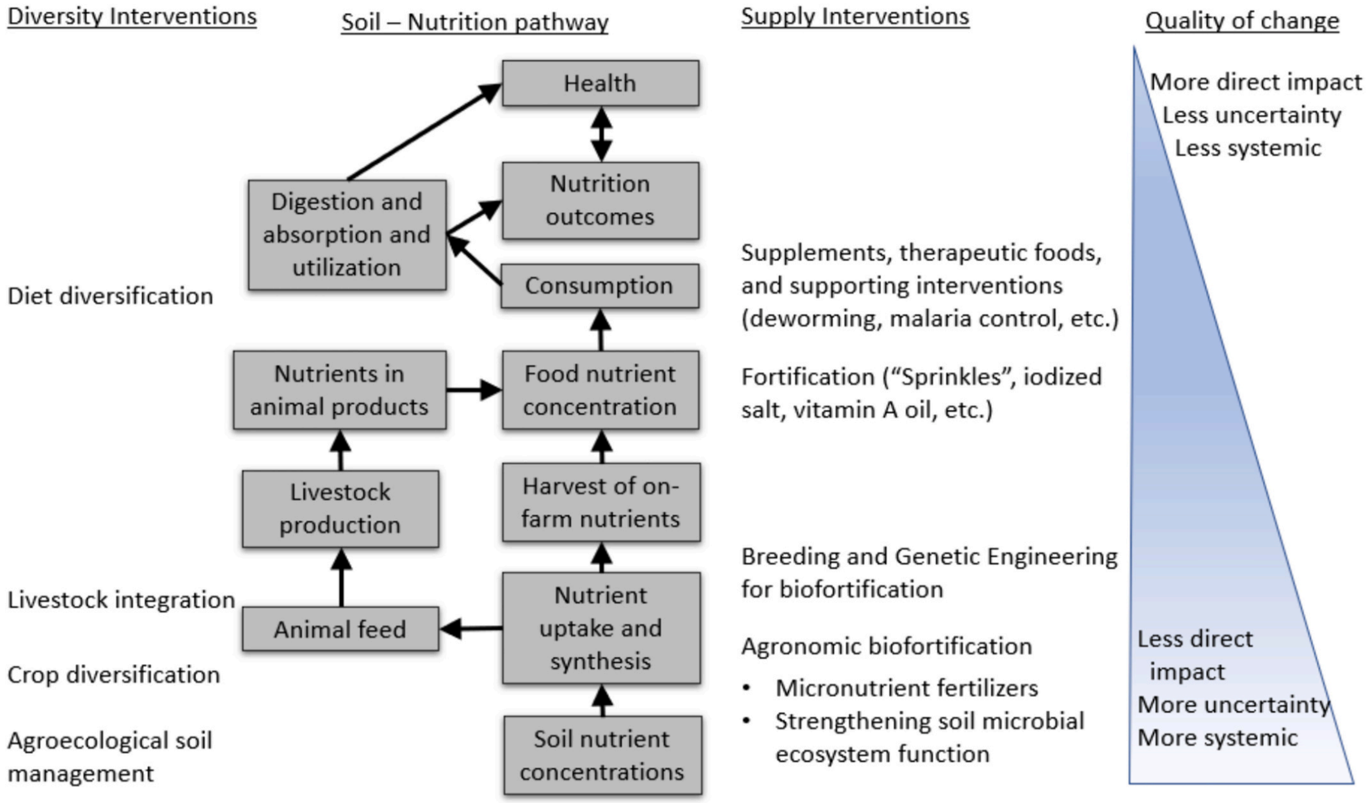

Fig. 1. The pathway from soil to nutrition and associated micronutrient deficiency interventions.

but when successful have the potential to be self-sustaining. Instead of directly providing specific micronutrients, an alternative strategy to reduce micronutrient deficiencies is to promote diet diversification (Malézieux et al., 2023), especially increasing frequent consumption of fruits, vegetables and animal products, which tend to already be rich in micronutrients. Such a strategy necessarily goes beyond dietary preferences to include availability and access to these nutrient dense foods, which are often more expensive than staples. Thus, agricultural diversification and creating equitable food systems can support dietary diversification, for a more systemic transformation with many ancillary benefits.

The Africa Research in Sustainable Intensification for the Next Generation (Africa RISING) project in East and Southern Africa included research on agronomy, plant breeding and nutrition. Linkages from soil to micronutrient deficiency were not part of the original design, however the integrated work to improve nutrition through dietary diversification, crop diversification and biofortification provides many lessons for future research. In this paper, we synthesize lessons from the literature and from Africa RISING research in Malawi and Tanzania about the connections between soil nutrients and micronutrient deficiencies. We also develop a research agenda for holistically assessing agricultural interventions to micronutrient deficiencies from the perspective of the five domains of sustainable intensification (productivity, economic, environmental, human condition and social).

After briefly describing the project's context (section 2), we summarize the literature connecting soil management to human nutrition for each of the major micronutrient deficiencies (section 3). After describing our methods (section 4), we synthesize our learnings with an overview of micronutrient deficiency interventions (5.1), and how various interventions tend to perform across the five domains of the Sustainable Intensification Assessment Framework (SIAF) (5.2). In section 6, we present guidelines for future research to effectively study soil-plant-nutrition connections, including key indicators to consider monitoring.

2. Project context

The Africa RISING Project was implemented between 2011 and 2023 in West Africa (Ghana, Mali), Ethiopia and in East and Southern Africa (Tanzania, Zambia and Malawi). The purpose of Africa RISING was to provide pathways out of hunger and poverty for smallholder farm families through sustainably intensified farming systems that sufficiently improve food, nutrition and income security, particularly for women and children, and conserve or enhance the natural resource base (https://africa-rising.net/). The project involved CGIAR centers, national research and extension institutions and farmers in each of the countries. Specifically, for East and Southern Africa, Africa RISING was implemented in the maize-dominated cereal−legume farming systems of Tanzania (Kongwa and Kiteto in Dodoma region and Babati in Manyara region), Malawi (Central Region), and Zambia (Eastern Province). In all three countries, Africa RISING scientists conducted research on agronomy and plant breeding by testing improved varieties of maize, legumes, vegetables and small grains under smallholder conditions and working collaboratively with farmers to increase yields with research on integrated soil fertility management (fertilizers, manures, intercrops, erosion control, etc.). Nutrition-specific research was also carried out in Tanzania and Malawi, but not Zambia; thus, for the rest of the paper we focus on these two countries.

Nutrition indices continue to be of public health concern in many countries including Tanzania and Malawi, especially for children as evidenced by high levels of key malnutrition indicators (Table 1). In Tanzania 35% of the disease burden falls on children younger than 5 years, and 11% of total global disability-adjusted life years (Black et al., 2013). In Malawi, childhood micronutrient deficiencies are high for zinc (60%), iron (21.7%) and vitamin A (10%) and poor health is also seen by inflammation with 57% of pre-school children having elevated C-reactive protein (National Statistical Office (NSO), Community Health Sciences Unit (CHSU) [Malawi], Centers for Disease Control and Prevention (CDC), and Emory University, 2016, Likoswe et al., 2021). Women of reproductive age are also a vulnerable group with 7.3% of non-pregnant women aged 15–49 in Tanzania being underweight and 28.8% having anemia (Ministry of Health, Community Development, Gender, Elderly and Children (MoHCDGEC) [Tanzania Mainland], Ministry of Health (MoH) [Zanzibar], Tanzania Food and Nutrition Centre (TFNC), National Bureau of Statistics (NBS), Office of the Chief Government Statistician (OCGS) [Zanzibar] and UNICEF, 2018). These challenges have been known for a long time; in 2013 it was estimated that maternal and child undernutrition caused 3.5 million annual deaths globally, with Malawi and Tanzania being the countries with the 8th and 23rd highest stunting rates (Black et al., 2013).

Table 1
Prevalence of various nutrition status indicators for children under 5 years in the project countries.

Indicator	Tanzania	Malawi
Stunting (height for age)	31.8%	37%
Underweight (weight for age)	14.6%	12%
Wasting (weight for height	3.5%	3%

Sources: National Statistical Office (NSO), Community Health Sciences Unit (CHSU) [Malawi], Centers for Disease Control and Prevention (CDC), and Emory University, 2016; Ministry of Health, Community Development, Gender, Elderly and Children (MoHCDGEC) [Tanzania Mainland], Ministry of Health (MoH) [Zanzibar], Tanzania Food and Nutrition Centre (TFNC), National Bureau of Statistics (NBS), Office of the Chief Government Statistician (OCGS) [Zanzibar] and UNICEF, 2018.

In Malawi, Africa RISING research focused on diversifying maize production through integration of legumes and livestock in Ntcheu and Dedza districts (Central Region), which have high stunting prevalence – 42.8% and 41.6% respectively (National Statistical Office (NSO), Community Health Sciences Unit (CHSU) [Malawi], Centers for Disease Control and Prevention (CDC), and Emory University, 2016). Maize is prioritized for caloric intake for food security, and the poorest tend to perceive protein sources as an optional luxury. Africa RISING held community events to raise awareness about legumes for nutrition and to encourage consumption through sharing local recipes. Maize productivity is limited by nitrogen and phosphorus. While nitrogen-fixing food legumes can improve both soil fertility and protein-rich nutrition, they are also limited by phosphorus. Pigeonpea (*Cajanus cajan*) is a shrubby legume that can access insoluble phosphates in the soil through the secretion of organic acids from the roots (Otani et al., 1996). In the Africa RISING study locations, Mzumara (2016) found that a soybean-pigeonpea intercrop system had 38% higher N-fixation than sole cropping and the overall P use efficiency was 75% higher than sole cropping. Such agro-ecological systems have the potential to increase on-farm production of diverse and nutritious foods and sustainably manage the soil.

The Africa RISING research activities in Tanzania focused on increasing production of maize, pigeon pea, groundnuts as well as consumption of pigeon pea and millet to address lack of access to proteins from animal source foods and address iron deficiencies. Research was conducted in Kongwa district, Dodoma Region (900-1000 m elevation and semi-arid with highly variable rainfall) and Babati district, Manyara region (1600-2200 m elevation and sub-humid). Dodoma is one of the six regions of Tanzania where chronic malnutrition exceeds 40%. Soils in Babati are mostly Ferralsols with limitations of N and P and micronutrients including Zn in specific places.

3. Methods

To develop this paper, an external consultant worked with a Ph.D. student to synthesize experiences from the other co-authors directly involved in Africa RISING, who are researchers involved in soil nutrient research and in human nutrition research in Malawi and Tanzania. The team of co-authors met monthly from January to September 2022 to develop the conceptual framework, compile lessons from various data collection efforts, suggest literature to review and generate ideas for the research agenda. Since that time the lead author developed the manuscript with regular feedback from the team of co-authors. In summary, this review combines lessons learnt from the Africa RISING East and Southern Africa project buttressed by evidence from previously conducted studies on the connections between micronutrient deficiencies and soils. To identify information on specific nutrition deficiency prevalence, the latest demographic health survey data were utilized. The impetus for this effort originated with an informal evaluation team within the project, who in late 2021 identified several gaps not fully addressed during the life of the project, where learning could be synthesized with the literature to guide future research.

4. Human nutrition - soil nutrient linkages

As agricultural yields of staple grains have increased, there is growing concern that nutrient density is declining, which can contribute to micronutrient deficiencies (Halweil, 2007; Fan et al., 2008). Many of the rural poor affected by these deficiencies cannot afford to regularly consume nutrient-dense animal source foods, relying instead on plant-based sources of vitamins and minerals, including staple grains, roots and tubers. However, in these low-income countries the consumption of nutrient-rich fresh produce is low, especially during the dry season (Giller et al., 2021).

Micronutrient deficiency is a general term that refers to a lack of essential vitamins and minerals required for healthy cellular functions. Micronutrient deficiencies affect around two billion people globally, and Vitamin A, iron, zinc, selenium, iodine, and folate deficiencies are the most widespread (Bailey et al., 2015; Muthayya et al., 2013; Zulu et al., 2022). Countries in sub-Saharan Africa exhibit the highest global levels of population-adjusted disease burden from micronutrient deficiencies (Muthayya et al., 2013). An analysis of minerals in national food supplies in Africa found that secondary and micronutrient defciency risks are highest for calcium, zinc, selenium, iodine, and iron (Joy et al., 2014), all of which have direct links to soils.

Recent efforts have demonstrated that micronutrient density in grains and pulses vary spatially, both at large scale (up to 100 km as in Botoman et al. (2022a)) and at the field scale (Manzeke et al., 2019). The causes of such variability include soil conditions (parent material, pH, organic matter) as well as broader environmental conditions (temperature, rainfall, slope), and these are specific to the micronutrients and crops (Gashu et al., 2021). Farm management practices, such as regenerative agriculture, have also been shown to influence micronutrient availability (Manzeke-Kangara et al., 2023). For example, grains and vegetables that are produced organically, tend to have higher concentrations of most nutrients and antioxidants (Hepperly et al., 2018), though in the context of depleted soils it is important to note that the addition of nitrogen and phosphorus, typically accomplished with chemical fertilizer, is critical for sustained food production.

In the following sub-sections, for each nutrient we describe its impact on health, the types of foods it can be found in and how the nutrient density of that food is impacted by the soil. Some nutrients are limited first by the natural distribution of such elements (zinc, iodine and selenium) and then by their bioavailability, while others may be abundant but with potentially low bioavailability or uptake (iron and calcium) and still others are synthesized by plants at varying levels depending on conditions (provitamin A carotenoids and folate).

4.1. Vitamin A

Vitamin A refers to a group of fat-soluble molecules and is an essential nutrient for mammals (Strobbe et al., 2018). Humans synthesize retinol from pro-vitamin A carotenoids present in green, yellow, and orange fruits and vegetables, including broccoli, spinach, carrots, squash, sweet potatoes, and pumpkins (Strobbe et al., 2018) or consume animal-based foods with pre-formed Vitamin A. Vitamin A deficiency (VAD) may result in a weakened immune system, deterioration of the light-sensitive rod cells essential for low light vision, most of which is sub-clinical, though in rare and severe cases VAD can lead to blindness (Bailey et al., 2015). Globally, more than four million children are deficient, including almost half of children under five years of age in sub-Saharan Africa (Lemoine and Tounian, 2020). Provitamin A carotenoids can be produced by plants on soils of varying levels of fertility, and increased soil organic matter may increase beta-carotene content (Montgomery and Biklé, 2021).

4.2. Iron

According to Lemoine and Tounian (2020), 60 % of children less than five years old in sub-Saharan Africa suffer from iron deficiency. Many smallholders depend on plant-based sources of iron, such as dry beans and dark green leafy vegetables. The concentration of iron in plants, which plays a role in photosynthesis and can affect yields, is influenced by climatic conditions and soil environments. Gerrano et al. (2022) found that iron levels in cowpea leaves depend on local soil properties, including a negative relationship between iron and manganese. Soil tillage practices may also influence the concentration of minerals in soils, with higher iron and zinc levels on the soil surface in no-till, while approaches with increased tillage, had higher mineral levels deeper in the soil profile (Zulu et al., 2022).

4.3. Zinc

Zinc is required for proper human growth, immune system development, enzyme activation, and neurobehavioral development (Peramaiyan et al., 2022). Zinc deficiency in mothers correlates with poor birth outcomes, including stunted growth, abnormal brain development, and pneumonia (Gerrano et al., 2022). Measuring zinc deficiency in populations is complicated due to wide regional variation (Belay et al., 2021) as well as the complicated nature of estimating serum zinc levels (serum concentration must be adjusted for age, gender and time of day (Belay et al., 2021) and still may not reflect zinc deficiency status), which has triggered efforts to identify biomarkers (Wang et al., 2021). Plant-based foods with high zinc concentrations include beans, lentils, chickpeas, and dark green leafy vegetables, though traces are found in whole grains.

African soils are particularly deficient in zinc relative to other micronutrients (Kihara et al., 2020), especially on sloped land, due to erosion. The link between land degradation and micronutrient deficiency is supported by research in Zimbabwe, which found that maize grain zinc concentration was positively correlated with land productivity (Manzeke et al., 2019). Botoman et al. (2022a) found that zinc grain concentrations in maize, the dominant dietary source of zinc in Malawi, varied with soil zinc levels and soil pH. The review by Mutambu et al. (2023) reports a mean maize zinc concentration of 21.8 mg kg^{-1}, well below the suggested target of 38 mg kg^{-1} to address dietary deficiencies (Klassen-Wigger et al., 2018). This is supported by our unpublished data from northern Tanzania, which found low zinc concentrations (below 38 mg kg^{-1}) in two-thirds of samples (Kihara, personal communication).

Zinc deficiency in crops can be caused by (1) soils with a low total zinc content; (2) limited bioavailability of zinc due to a high pH soil or to its adsorption to certain types of iron oxides; (3) low levels of soil organic matter; (4) the presence of nitrogen, sodium, calcium, magnesium, and phosphates in soil; and (5) restricted root growth due to soil compaction or other environmental factors (Noulas et al., 2018; Recena et al., 2021). Experiments in Malawi with adding zinc fertilizers have shown large increases in maize yield (11%) as well as 15% increased grain zinc concentration (Botoman et al., 2022b), while research in

Kenya showed that zinc concentration in common beans was more responsive to zinc fertilization than maize (Mutambu et al., 2023).

4.4. Selenium

Selenium is a critical component of selenoproteins, which are involved in a multitude of biological processes including antioxidant protection, DNA synthesis and the formation of thyroid hormones (Hogan and Perkins, 2022). Selenium deficiencies are associated with increased rates of cancer and higher prevalence of myocarditis (Combs, 2022). Selenium deficiency risks are potentially high in many settings in Africa and are geospatially dependent (Ligowe et al., 2020). Animal products tend to be rich in selenium, which in Malawi translates into increased risk of deficiency for low-income groups (Phiri et al., 2019). A nationally representative survey found lower risk of selenium deficiency near Lake Malawi where more fish is likely to be consumed and in urban areas, which have greater food expenditure, enabling more diverse diets (Phiri et al., 2019). Plant-based foods high in selenium include whole grains, legumes and Brazil nuts. Selenium biofortified foods have been found to be enriched in antioxidants, providing an additional benefit to human health (Schiavon et al., 2020).

Soil selenium content is highly variable. The primary factor in a soil's selenium concentration is its parent material, with lower levels from igneous rocks and higher levels from sedimentary material, especially Cretaceous shales (Schiavon et al., 2020). A comprehensive review found that variations in the soil selenium concentration influence crop concentrations, intake levels and biomarkers of selenium concentrations (Mutonhodza et al., 2022). Ngigi et al. (2020) examined eight locations in Kenya's central highlands and found selenium intake among women and children associated with the soil's pH, organic matter, and phosphorus content.

Even where selenium is present in the soil, it may not be bioavailable to the plants due to other soil conditions. At a higher pH, selenium is more bioavailable because its oxidation state shifts to selenate (Se^{6+}), which is more water soluble and less easily adsorbed by mineral complexes (Joy et al., 2014). Research in Malawi found lower selenium deficiency risk on Vertisols due to lower pH (Phiri et al., 2019). Soil organic matter contributes to bioavailability through decreased leaching and erosion and through providing soil phosphates that cause desorption of selenite (Se^{4+}) bound to mineral complexes (Joy et al., 2014).

4.5. Iodine

Iodine is essential for the synthesis of thyroid hormones and deficiency may result in thyroid, metabolic, and developmental diseases, as well as cancer (Winder et al., 2022). Salt iodization is critical for addressing iodine deficiency and has become common practice globally, but when not used universally, deficiencies persist where soils are iodine deficient (Ligowe et al., 2021; Winder et al., 2022). Within some African countries, insufficient iodine intake in pregnancy happens even in countries where the general population consumes adequate iodine (Businge et al., 2021). Some plant-based non-marine iodine-rich foods include strawberries, potatoes, green beans and leafy vegetables.

4.6. Folate

Folates are a group of water-soluble B vitamins and deficiency may result in neural tube defects, megaloblastic anemia, and an increased risk of Alzheimer's, cardiovascular and coronary diseases, stroke, and cancer (Strobbe and Van Der Straeten, 2018). Beans and green leafy vegetables are naturally dense sources of folate (Kiran et al., 2022). Folate levels in crops depend on nutrient availability, temperature, and soil quality, such as when nitrogen, phosphorus, and boron are plant-available in the soil (Mozafar, 1994).

4.7. Calcium

Calcium plays a fundamental role in the development of healthy bones and teeth (Knez and Stangoulis, 2021). Based on calcium supplies in national food systems, 54 % of the population of Africa were at risk of inadequate dietary calcium intake (Joy et al., 2014; Knez and Stangoulis, 2021). Plants with high concentrations of calcium include leafy green vegetables and broccoli (Martínez-Ballesta et al., 2010). In Africa, important sources of dietary calcium include root vegetables, dairy products, and fish (Joy et al., 2014).

Calcium plays an essential role in processes that regulate a plant's growth and resilience to environmental stress (Waraich et al., 2011). Factors that may decrease calcium bioavailability in soils and uptake by crops include increased salinity and drought, especially when water-stress occurs during the later stages of fruiting (Martínez-Ballesta et al., 2010).

5. Assessing strategies for addressing micronutrient deficiencies

Given this growing body of evidence that soil management influences micronutrient content in foods, there are increasing efforts to use agriculture to reduce hidden hunger. However, the further the intervention from dietary intake, the more difficult it is to assess its effectiveness (Fig. 1). In the following section we synthesize the learnings from Africa RISING with the literature regarding micronutrient interventions. This is followed in 5.2 by applying the SI assessment framework to holistically assess micronutrient deficiency interventions.

5.1. Micronutrient deficiency interventions

Non-agricultural solutions to micronutrient deficiencies include supplements and fortifying commonly purchased foods. Notable successes include iodized salt and to a lesser extent Vitamin A cooking oil (Bailey et al., 2015; Low et al., 2017; Strobbe et al., 2018). However, poor rural populations who carry the burden of global micronutrient deficiencies typically minimize purchases of many potentially fortified foods (Burchi et al., 2011), or, if possible, they process raw unfortified ingredients. Research to model large-scale vitamin A fortification in Malawi found that all potential fortification vehicles would not significantly reach the rural poor (Tang et al., 2022. Home fortification may be able to reach such populations using products like "Sprinkles" – a micronutrient packet that can be added to a child's food, especially during the nutritionally vulnerable period of 6–24 months of age. A review by Dewey et al. (2009) found home fortification to be safe, effective and cost-effective, especially for anemia, but found that improvements in child growth required adding protein and fat to the diet as well. Supplements can be costly but have proven to be a worthwhile investment in some cases, especially when targeted and when consumption can be assured, such as large doses of vitamin A provided to infants and mothers at health centers (Ross, 2002). However, these programs depend on access to health care systems, which many of the rural poor may not have. For example, using Demographic and Health Survey data from 49 countries, Tang et al. (2023) found that Vitamin A supplementation for children was not equitably delivered in many countries.

5.1.1. Genetic biofortification

In an effort to increase the supply of micronutrients to smallholder farmers, scientists employ breeding and genetic engineering to increase the concentrations of micronutrients in staple foods. Genetic biofortification is a high-cost investment using conventional breeding or transgenic approaches to develop varieties with greater concentrations of micronutrients (Welch and Graham, 2004) as well as Quality Protein Maize. Biofortified maize, rice, wheat, beans, pearl millet, sweet potato, and cassava with higher iron, zinc, or Provitamin A have been introduced in numerous developing countries (Kiran et al., 2022; Nkhata et al., 2020) enabling increased Provitamin A intake in smallholder farmers' children (Low et al., 2017). Challenges include achieving competitive yields and reducing post-harvest losses of easily oxidized carotenoids (Nkhata et al., 2020).

For cereals, plant breeding for yields have historically led to a dilution of nutrients in the crop (Fan et al., 2008). Interestingly, Velu et al. (2019) found that yield and micronutrient concentrations are controlled via distinct genetic pathways, indicating that it should be possible to breed for both increased yield and micronutrient content.

Genetically fortifying staple foods has the potential to sustainably provide micronutrients without requiring dietary changes (Strobbe et al., 2018). However, this oversimplifies the complexity of technology adoption and ignores the cultural reticence to even subtle changes in staple foods, such as color and taste. Provitamin A golden rice, which is available as a cost-effective solution, has faced social, cultural, and political concerns around genetic modification (Kiran et al., 2022). In Africa, consumer preference for white over yellow corn, as well as consumers' inability to distinguish between biofortified and conventional products of the same color, poses challenges to adoption of biofortified corn varieties (Kiran et al., 2022).

Biofortified bean varieties, selected for high levels of iron and zinc were introduced in Malawi in 2009 (Munthali et al., 2020) but barriers include low awareness on the importance of iron for health, misunderstanding about the term "biofortification", and an absence of marketing their nutritional value (Hummel, 2020). Branding these beans with a local name that connotes health could be combined with nutritional training to increase utilization.

Furthermore, producing these biologically fortified crops on degraded soils is especially challenging, and improved soil management is required to maximize the genetic potential of biofortified varieties. Evidence from Pakistan highlights that zinc concentrations in biofortified wheat varieties depend on environmental and management factors (Zia et al., 2020).

5.1.2. *Agronomic biofortification*

Alternatively, food crops may be biofortified agronomically by providing them with the right conditions to develop high concentrations of micronutrients (Burchi et al., 2011). Contextualized fertilizer application, combined with the ecological management of soil organic matter, allows crops to obtain minerals for production of nutrient dense foods (Barker and Stratton, 2020; de Valença et al., 2017; Kihara et al., 2020).

Agronomic biofortification using relatively low-cost micronutrient fertilizers (Cakmak et al., 2010) has been shown to profitably improve yields in sub-Saharan Africa (Kihara et al., 2017) and to increase micronutrient concentrations in the edible parts of plants (Kihara et al., 2020).

Application of micronutrients to the soil or plant leaves can increase grain micronutrient concentration (de Valença et al., 2017), with studies demonstrating foliar applications of iodine, zinc, and iron increasing micronutrients in beans and grains (Kiran et al., 2022; Stangoulis and Knez, 2022; Ligowe et al., 2021). Finland effectively decreased their population's selenium deficiency by adding that element to agricultural fertilizers (Alfthan et al., 2015) and recent trials in Malawi show that the same could be achieved in SSA (Joy et al., 2022). Application of iodine to fodder increases iodine content in animal products, subsequently improving human nutrition (Nube and Voortman, 2006).

Micronutrient fertilizers can also help crops grow better, such as by overcoming biotic stresses and deficiencies of minerals that are not of significant public health concern, such as boron, molybdenum, and copper (Kihara et al., 2020). In Finland, zinc and iron sprays applied to wheat promoted root growth and resistance to pathogens (Kiran et al., 2022). Application of zinc through seed priming, foliar sprays, or soil fertilizers may improve maize seed germination (Kiran et al., 2022). Maize has reduced lodging and higher yields when 150-220 g/ha of selenium are applied to Se-deficient soils (Wang et al., 2022). See 4.3 above for a summary of research findings on zinc fertilizer use.

Ecologically based agronomic biofortification strategies, such as composting and inoculating with farmer-grown mycorrhizal fungi, may enable low-income farmers to increase micronutrient density in the edible portions of crops (Manzeke-Kangara et al., 2023). Managing mycorrhizal fungi in crops is complex but there is potential for improved plant nutrition, protection from soil pathogens and stress tolerance (Rillig et al., 2016). Research on adding iron, zinc and selenium in combination with beneficial bacteria and fungi showed improved uptake of these nutrients due to the microbes making them more soluble (Szerement et al., 2022), though it should be noted that regulation of inoculants sold for such purposes is minimal, raising concerns about quality control. Selection of rootstock and mycorrhizal association may increase nutrient uptake in fruits (Barker and Stratton, 2020). The presence of arbuscular mycorrhizal fungi in soils where organic practices such as compost addition are used may also contribute to improved concentrations of calcium in plants (Kelly and Bateman, 2010). A complementary practice, agricultural diversification, can support soil health and thus nutrition.

5.1.3. *Agricultural diversification*

Agricultural diversification can support nutrition through greater dietary diversity (Burchi et al., 2011), especially if nutrient dense crops are added for nutrition purposes (Low et al., 2017). Integrating livestock also plays a critical role, such as with ultra-poor farmers in Kenya having better nutrition if they raise poultry (Demeke et al., 2016). The connection of production diversity to nutrition can be indirect, such as where increased legume production in Malawi led to greater consumption of diverse purchased foods, due to higher incomes (Azzarri et al., 2022). A meta-analysis of 45 studies found small positive effects between production diversity and dietary diversity, with larger effects in sub-Saharan Africa, but not sufficient to assume that farm diversification will improve smallholder nutrition (Sibhatu and Qaim, 2018). In Tanzania, the key determinants of dietary diversity included crop diversity, nutrition training, and when women have more control over household resources (Ochieng et al., 2017), showing the need for an interdisciplinary approach.

Agricultural diversification itself depends on complex social dynamics (access to information), environmental bounds (precipitation), and economic limits (farm size, Zongho et al., 2022). Additional challenges include seasonality of food availability, the adoption of agricultural technologies, and access to markets, water, and land (Jordan et al., 2022). Care must be paid to intra-household power dynamics to ensure that diversification does not overburden female farmers (Bezner Kerr et al., 2019). Nevertheless, a diversified approach can increase food system sustainability when locally adapted solutions are combined with inclusive social and environmental standards (Snapp et al., 2019).

Beyond the farm boundaries, landscape level diversity can contribute to nutrition through direct consumption of forest foods and through how forests may support more productive agriculture, though these effects are not universal (Baudron et al., 2019) Deforestation in Tanzania was associated with an 11% decline in daily average intake of fruits and vegetables, but forest fragmentation led to increased consumption, probably due to greater access by those inhabiting newly cleared plots (Hall et al., 2022). Agricultural intensification often threatens forests; sustainable intensification needs to go beyond preserving trees to support social systems that will ensure equitable access to forest foods, especially by women and children (Koffi et al., 2020).

5.2. *SI assessment framework and micronutrient deficiencies*

Sustainability assessments provide a systems perspective through explicit consideration of a wide range of goals across temporal and spatial scales. The Africa RISING project was instrumental in developing the Sustainable Intensification Assessment Framework (SIAF, Musumba et al., 2017). The SIAF provides a menu of indicators for comparing

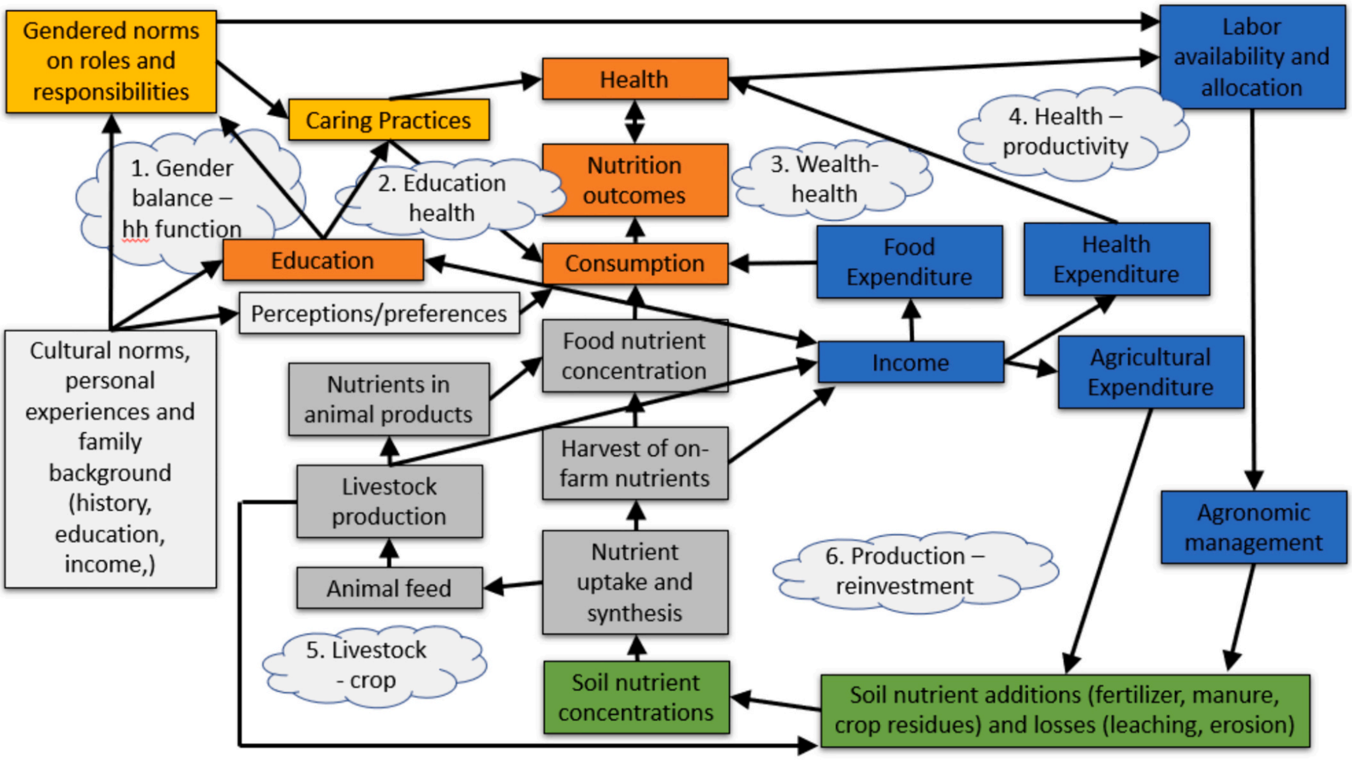

Fig. 2. Interactions and feedback loops with key factors across the five domains of sustainable intensification.
Note: The feedback loop labels are in cloud icons. The boxes are color-coded to the domains of SI as follows: Productivity – gray, Economic – blue, Environmental – green, Human Condition – orange, and Social – Yellow.

agricultural interventions across five domains: productivity (e.g. yield), economic (e.g. profitability), environmental (e.g. erosion, biodiversity), human condition (e.g. nutrition, food security, education) and social (e.g. gender equity). The connections between soil and nutrition run clearly from the environmental domain (soil conditions), through the productivity domain (agricultural production) to the human condition domain (nutritional outcomes). The connections along the pathway are mitigated by both the economic domain and the social domain (Fig. 2). Thus, any agricultural intervention to reduce micronutrient deficiencies will have impacts across all five domains and therefore can be assessed and compared using the SIAF.

5.2.1. *Feedback loops on the soil to nutrition pathway*

Nutrition-sensitive agriculture is a food-based approach that combines increasing the production of nutritionally rich foods with promotion of dietary diversity and food fortification to overcome malnutrition and micronutrient deficiencies (Food and Agriculture Organization of the United Nations, 2015). Recent reviews on nutrition-sensitive agriculture have pointed out how farming practices can influence nutrition positively or negatively through five major pathways 1) production of nutritious foods, 2) income to buy food or pay for health care, 3) knowledge on nutrition, health and care, 4) women's empowerment through intrahousehold decision-making and time allocation, and 5) strengthening existing institutions for health, agriculture and education (Sharma et al., 2021).

The three of these pathways most directly related to agricultural interventions (production, income and women's empowerment) can also be represented as reinforcing feedback loops (loops 1, 3 and 4 in Fig. 2), where gains or losses in health affect those factors' influence on nutrition in the future. In addition, agroecology of the soil is another fundamental, including crop residue management, livestock interactions and appropriate fertilizer applications for each crop and soil type (feedback loops 5 and 6 in Fig. 2).

Likewise, nutrition education is fundamental, including the nutritional needs of household members by age and health status, micronutrient content of various foods, and how preparation impacts nutritional quality (feedback loop 2 in Fig. 2). There are also many interactions across food components that can enhance or inhibit nutrient uptake by the human body. A diet with insufficient Vitamin A and iron makes the effects of iodine deficiency worse (Montgomery and Biklé, 2021). Iron and zinc are found in the same foods, especially animal products, so those deficiencies are often correlated. Ascorbic acid enhances iron bioavailability depending on BMI status (Cepeda-Lopez et al., 2015) while phytates from plants inhibit iron and zinc absorption by the body (Hallberg et al., 1989). Processing is needed to reduce phytates for some crops, such as millets, which are traditionally fermented in porridge and local beer. Such interactions are essential to consider when evaluating micronutrient intervention strategies.

5.2.2. *Comparing agricultural micronutrient interventions with SIAF*

There are competing perspectives on how best to address micronutrient deficiencies and the SIAF can be used to holistically assess each intervention across the five domains (Musumba et al., 2017). Table 2 provides examples of considerations for each domain and intervention, though it is not a comprehensive list. Of course, the actual performance of any intervention will be context-specific, but these generalizations illustrate the holistic nature of the tool. Using the SIAF, it is possible to collect data for any given context on indicators across all five domains and compare approaches to address micronutrients. The goal of such an exercise would not be to select one winner, but rather to identify strengths and weaknesses so that interventions can complement each other.

Within the Africa RISING project the SIAF has been shown to be useful for holistically assessing legume interventions for improving both soil and nutrition (e.g. Snapp et al., 2018). We summarize that here to provide an example of its use before applying it to future research to

Table 2
Nutritional interventions compared across the five domains of the SI Assessment Framework.

	Diet diversification	Genetic biofortification	Agronomic biofortification	Agricultural diversification
Nutrition outcomes	More direct impact than other three because consumption is assured	Potential for embedding nutrients into staple foods, conditional on environmental factors	Potential for embedding nutrients into staple foods, conditional on environmental factors	May not lead to diet diversification or overcome mineral deficiencies
Productivity impacts	Creates demand for the production of diverse foods	Positive if nutritional traits are effectively coupled with agronomic traits. Negative if one variety dominates causing susceptibility to disease or pests	Potential positive side effects from effective fertilizer use or organic input use.	Positive side effects through rotations and resilience to shocks
Environmental impacts	Indirect positive through associated agrobiodiversity	Reduced agrobiodiversity if new variety becomes dominant	Positive if soil nutrient inputs are not excessive and not leading to emissions	Positives for nutrient cycling, reduced pest build up, microhabitat creation. Negative if vegetables require higher pesticide use
Social factors	Complex cultural factors influence dietary preferences	Adoption of new varieties tends to be slow. Strong cultural preferences for food appearance. Policy and social resistance to genetically modified crops in SSA	Low education on soil nutrient dynamics. Equity concerns with purchased inputs. Labor allocation concerns for organic inputs.	More crops to manage means more complex training requirements for improved production
Economic factors	Strategies needed to help the poorest consumers access nutritious food	High investment cost in supply chain may not be recoverable through subsistence farmers. Equity concern for poorest farmers.	Micronutrient fertilizer costs compared to “invisible” benefits	Goes against trends toward specialization and economies of scale

assess agricultural interventions for micronutrient deficiencies. Legume diversification by smallholder farmers is complicated by economic factors, such as high seed costs, limited and uncertain market access, unstable and highly variable prices (Bezner Kerr et al., 2007). Africa RISING employed a Mother-Baby Trial (MBT) approach for farmer-led participatory research to introduce and test the performance of legume intercrop (Snapp et al., 2018; Snapp et al., 2019). Likewise, the Africa RISING project used a community learning approach to nutrition with women and children participating in culinary demonstrations of common dishes and supplementary foods, while also receiving training in child nutrition, water, sanitation, and hygiene (Chowa et al., 2021). Important synergies for pigeon pea-diversified farming systems include reduced fertilizer use, soil fertility building properties, improved protein production, and higher ratings of technologies by women farmers (Snapp et al., 2018).

6. Research agenda for soil-plant-human nutrition

Effective research to assess agricultural interventions to address micronutrient deficiencies will require a careful design that holistically considers all five domains in the SIAF (Musumba et al., 2017). The experience from Africa RISING also shows that simply having all the elements of soil science, agronomy, plant breeding, nutrition and gender together in a project is insufficient to thoroughly understand soil to nutrition linkages. Instead, to evaluate context-specific interventions for a particular micronutrient deficiency will require identifying a clear pathway from the agricultural intervention to the nutritional outcomes. For example, consider the evidence gaps that need to be researched to effectively assess how high-zinc beans could reduce zinc deficiency in Malawi and Tanzania. These knowledge gaps are presented in order from soil to plant to nutritional outcomes.

First, there is need for a more thorough understanding of how soil and environmental factors influence the zinc content of beans being grown in the target location, which would require at least surveying bean farmers about their practices, sampling their soils and beans, and linking that with climatic data. One product of such research would be maps that could facilitate targeting interventions. In this example, a high-zinc variety could be targeted at areas where soil zinc seems to be available, but bean zinc content is low. An excellent example of what can be learned from mapping soil nutrients and food nutrient levels is Gashu et al. (2021). Another focus of such a survey would be to identify agronomic practices leading to higher zinc concentrations in beans, with special attention to how soil organic matter is being managed, as done by Manzeke-Kangara et al. (2023).

Next, assuming a high-zinc bean variety has been developed, its performance would need to be assessed across the range of environments and management practices used by smallholders, knowing performance may be site-specific (Zia et al., 2020). In locations where soil zinc levels are low, it would make sense to research how agronomic biofortification (zinc fertilizer types and application rates) performs in combination with high-zinc bean varieties. Experimental designs need to be sufficiently powered to detect the relatively small effect sizes in the micronutrient concentration of the harvested portion (Botoman et al., 2022b). Once used at scale, the grain zinc content needs to be tested across the wide range of conditions, as done by Glahn et al. (2020) for high-iron beans in East Africa, which found little difference in iron levels between biofortified non-biofortified varieties. Assessing bioavailable zinc in the cooked bean is also important, though typically done when developing the variety. Once there is sufficient use of the high-zinc bean variety, then it will be possible to research the population-level health impact.

This example highlights the discipline-specific research gaps at various points in the soil to health pathway (plant breeding, agronomy, agricultural economics, nutrition) and at various stages of development of a genetic biofortification intervention. For whichever discipline or stage of development, the research should be complemented with an interdisciplinary approach for holistic analysis of the side effects across domains. To facilitate such data collection, lists of indicators, metrics and measurements are presented by domain in Tables 3 and 4. This interdisciplinary approach helps to identify complementarities and tradeoffs across the categories of interventions.

The most obvious tradeoff is when one type of agricultural micronutrient deficiency intervention is emphasized to the exclusion of others, which naturally tends to follow disciplinary boundaries (e.g. plant breeders emphasizing genetic biofortification, agronomists emphasizing biofortifying with micronutrient fertilizers and agroecologists emphasizing agricultural diversification). Where genetic biofortification is pursued, it should be embedded within a framework of nutrition education (to spur demand), participatory evaluation (to adjust the variety to local needs) and agroecology (to ensure performance can be sustained in smallholder conditions). Where agronomic fortification is pursued, it would benefit from the same guidelines, though the technology (e.g. a new fertilizer or soil management practice) may be more amenable to post-implementation adjustments than a new variety, making on-going participatory evaluation important.

Table 3
Indicators, metrics and measurement methods connecting soil nutrients to human nutrition.

Point in chain from soil to health	Outcomes	Indicators	Metrics	Measurements
Nutrients in food	Crop/food nutritional quality	Nutrient content	Nutrient concentrations in edible portion of crop	Laboratory analysis of nutrients in edible portion of crop (e.g. inductively coupled plasma mass spectrometry for Zinc in grain)
			Nutrient concentrations in prepared foods	Laboratory analysis of nutrients in prepared food Food composition tables
			Bioavailable nutrient concentrations	
Human nutrition	Dietary micronutrient adequacy	Consumption of nutritious food	Nutrient supply at household level	Household Consumption and Expenditure Surveys
			National food availability	Food balance sheets
			Population/Individual dietary intake	Diet Record 24-h recall (Quantitative or Qualitative) Food frequency questionnaire
			Food consumption score	Food group consumption questionnaire
			Dietary diversity score – household, women or children focused	Dietary diversity questionnaire to calculate Household Dietary Diversity Scores, Minimum Dietary Diversity for Women (MDD—W) and Minimum Dietary Diversity (MDD) for children 6–23 months
Human nutrition	Nutritional Status	Micronutrient levels in the human body	Biomarker of status	Various tests using biological samples (blood or urine samples or other appropriate in vivo tests) for specific micronutrients (e.g. hemoglobin for anemia)
			Dietary intake assessments	Frequency of consumption of specific foods or quantitative assessments of food intake, extrapolating to micronutrient intake
			Anthropometric measures	Biometrics: height, length, weight, body mass index (BMI), head circumference, skin fold thickness, and arm circumference
			Clinical assessments	Physical examination of symptoms of micronutrient deficiencies such as bleeding gums, edema, mouth ulcers, goiter, night blindness Self-reported outcomes: tiredness, diarrheal disease,
Human nutrition	Nutritional Status	Child nutrition outcomes	Nutritional status of children in a household or population (% wasting, % underweight, % stunting, % overweight or obese), % Kwashiorkor	- Weight for height z-score (short term) - Weight for age z-score (medium term) - Height for age z-score (long term) - Kwashiorkor indicators - Birth weight - Head circumference - Health center records - Surveys
Human nutrition	Nutritional Status	Maternal nutritional outcomes	Maternal micronutrient status (See above)	See micronutrient levels above
			Maternal weight change during pregnancy	
			Fetal growth	Direct weight measurements
			Birth weight of child	Fundal height measurements or ultrasound
			Birth outcomes	Health center records Anthropometrics of newborn
Health outcomes	Disease	Disease prevalence	Prevalence of micronutrient deficiency related diseases	Health center records Surveys (such as Epidemiological or demographic health surveys

Table 4
Social, economic, agronomic and environmental indicators, metrics and measurement methods of likely relevance for research connecting soil nutrients to human nutrition (adapted from Musumba et al., 2017).

Domain	Point in chain	Indicators	Metrics	Measurements
Social	Nutrients in food	Accessibility	Equality of access to nutritious food in market by vulnerable groups	Survey of market use patterns by vulnerable groups measuring incidence and frequency of purchases
Economic	Nutrients in food	Affordability	Cost of nutritious foods as percent of income	Costs in local markets of foods containing micronutrients of interest compared to household income
			Market supply of nutritious food	Volume and frequency in local markets of foods containing micronutrients of interest
Economic	Post-production / pre-consumption	Income and expenditure	Sales of crops/animal products and expenditure on nutritious foods	Survey of harvest sale quantities and prices Survey of food purchases and prices
Environment	Nutrients in food	Availability	Landscape supply of nutritious food	Quantities of wild foods gathered by season
Productivity	Nutrients in harvest / animal products	Yield of nutrients	Micronutrient production (g/ha) at plot or farm level	Laboratory analysis of harvest / animal product (most precise) Variety/breed-specific micronutrient levels in food composition tables Crop/animal-specific micronutrient levels from food composition tables (least precise)
Productivity	Livestock production	Animal productivity	Animal product per hh (product/hh/yr)	Recall survey and production measurements
Productivity	Plant production	Plant growth	On-farm availability of diverse food crops	Survey of all crops, including intercrops and border crops
			Yield of crops	Farmer recall or crop cut to estimate yield, measuring field size with GPS
Productivity	Plant production	Micronutrient uptake/ synthesis	Micronutrients in plant tissue	Laboratory tests of leaf, stem or root samples
Environment	Soil nutrients	Soil micronutrients	Bioavailability of soil mineral micronutrients	Laboratory tests of soil including pH and ionic form of some minerals (Fe, Se, Zn)
	Soil health	Soil micronutrients	Concentration of soil mineral micronutrients	Laboratory tests of soil for total quantities of minerals (Fe, Se, Zn, Ca, I, etc.)
	Soil health	Erosion	Soil loss (tons/ha/year)	Direct measurement, modeling or survey
	Soil health	Soil biology	Soil carbon levels	Total carbon or active carbon soil test
			Soil microbial diversity	Abundance and diversity of mycorrhizae
	Soil health	Soil physical quality	Soil aggregate stability and bulk density	Soil tests

The use of indicators across all five domains of the SIAF facilitates interdisciplinary analysis, including key social indicators often neglected by biophysical researchers. Substantial evidence demonstrates that more equal access to and control over assets across genders raises agricultural output, increases investment in child education, improves visits to health facilities for infants, raises household food security, and accelerates child growth and development (Oniang'o and Mukudi, 2002). Gender transformative approaches therefore must be a critical component of any effort to reverse micronutrient deficiencies through agriculture.

Recent examples of interdisciplinary perspectives on micronutrient deficiencies call for increased emphasis on dietary diversification (van Ginkel and Cherfas, 2023; Malézieux et al., 2023), highlighting the high cost and uncertain outcomes of genetic biofortification, including the challenges with lower yield but more nutrient dense varieties as well as the downsides of reduced agrobiodiversity. As Burchi et al. (2011) state, the emphasis should be "on interventions that address food and nutrition security as part of a wider multi-sector strategy tailored to diverse conditions of major agroecological, socioeconomic and epidemiological situations."

A critical link between agroecology and nutrition involves an emphasis on local knowledge systems. When combined with attention to gender, participatory approaches can augment the sustainability of agroecological interventions (Bezner Kerr et al., 2019). Encouraging farmers and other stakeholders to effectively collaborate in all aspects of the research process (design, data collection, analysis, dissemination) is a complex challenge that often works best in the context of a long-term relationship between international and national researchers, private sector stakeholders, extension and communities.

7. Conclusion

The evidence indicating the potential for agricultural interventions to reduce micronutrient deficiencies is growing steadily. However, effectively assessing causal effects across the soil-plant-food-nutrition pathway is a major challenge. Our synthesis of the literature and project experience suggests a framework that can guide the selection of indicators for holistically assessing interventions. A clear message from the Africa RISING project is that interdisciplinary research driven by a clear soils-to-nutrition research pathway, combined with participatory interventions for agricultural and nutrition education are needed for effective learning about the connections between soil nutrient levels and human micronutrient deficiencies. Such long-term systemic action research will require a careful balance between flexibility and accountability. Flexibility is needed to ensure that cultural change is responsive to sociocultural dynamics; and accountability is needed for projects to make real contributions to the evidence base for improving the ecological, economic, and social conditions of smallholder farmers.

CRediT authorship contribution statement

Philip Grabowski: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Conceptualization. **Douglas Slater:** Writing – original draft, Visualization, Formal analysis, Conceptualization. **Wanjiku Gichohi-Wainaina:** Writing – review & editing, Writing – original draft. **Job Kihara:** Writing – review & editing, Writing – original draft, Conceptualization. **Regis Chikowo:** Writing – original draft, Conceptualization. **Agnes Mwangwela:** Writing – original draft, Conceptualization. **Dalitso Chimwala:** Writing – original draft, Conceptualization. **Mateete Bekunda:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

None of the authors have any competing or non-financial interests to declare.

Data availability

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References

Alfthan, G., Eurola, M., Ekholm, P., Venäläinen, E.R., Root, T., Korkalainen, K., Selenium Working Group, 2015. Effects of nationwide addition of selenium to fertilizers on foods, and animal and human health in Finland: from deficiency to optimal selenium status of the population. J. Trace Elem. Med. Biol. 31, 142–147.

Alloway, B.J., 2009. Soil factors associated with zinc deficiency in crops and humans. Environ. Geochem. Health 31 (5), 537–548.

Azzarri, C., Beliyou, H., Letta, M., 2022. Plant different, eat different? Insights from participatory agricultural research. PLoS One 17 (3).

Bailey, R., West Jr., K., Black, R., 2015. The epidemiology of global micronutrient deficiencies. Ann. Nutr. Metab. 66 (Suppl. 2), 22–33.

Barker, A., Stratton, M., 2020. In: Srivastava, A., Hu, C. (Eds.), Nutrient Density of Fruit Crops as a Function of Soil Fertility, p. 31. WOS:000610722200003.

Baudron, F., Tomscha, S.A., Powell, B., Groot, J.C., Gergel, S.E., Sunderland, T., 2019. Testing the various pathways linking forest cover to dietary diversity in tropical landscapes. Front. Sustain. Food Syst. 3, 474255.

Belay, A., Gashu, D., Joy, E., Lark, R., Chagumaira, C., Likoswe, B., Zerfu, D., Ander, E., Young, S., Bailey, E., Broadley, M., 2021. Zinc deficiency is highly prevalent and spatially dependent over short distances in Ethiopia. Sci. Rep. 11 (1), 6510.

Bezner Kerr, R., Snapp, S., Chirwa, M., Shumba, L., Msachi, R., 2007. Participatory research on legume diversification with Malawian smallholder farmers for improved human nutrition and soil fertility: smallholder diversification with legumes. Exp. Agric. 43 (4), 437–453.

Bezner Kerr, R., Rahmanian, M., Owoputi, I., Batello, C., 2019. Agroecology and Nutrition: Transformative Possibilities and Challenges, pp. 53–63.

Black, R.E., Victora, C.G., Walker, S.P., Bhutta, Z.A., Christian, P., De Onis, M., Uauy, R., 2013. Maternal and child undernutrition and overweight in low-income and middle-income countries. Lancet 382 (9890), 427–451.

Botoman, L., Chagumaira, C., Mossa, A.W., Amede, T., Ander, E.L., Bailey, E.H., Nalivata, P.C., 2022a. Soil and landscape factors influence geospatial variation in maize grain zinc concentration in Malawi. Sci. Rep. 12 (1), 7986.

Botoman, L., Chimungu, J.G., Bailey, E.H., Munthali, M.W., Ander, E.L., Mossa, A.W., Nalivata, P.C., 2022b. Agronomic biofortification increases grain zinc concentration of maize grown under contrasting soil types in Malawi. Plant Direct 6 (11), e458.

Burchi, F., Fanzo, J., Frison, E., 2011. The role of food and nutrition system approaches in tackling hidden hunger. Int. J. Environ. Res. Public Health 8 (2), 358–373.

Businge, C., Longo-Mbenza, B., Andre, P., 2021. Iodine nutrition status in Africa: potentially high prevalence of iodine deficiency in pregnancy even in countries classified as iodine sufficient. Public Health Nutr. 24 (12), 3581–3586.

Cakmak, I., Kalayci, M., Kaya, Y., Torun, A.A., Aydin, N., Wang, Y., Horst, W.J., 2010. Biofortification and localization of zinc in wheat grain. J. Agric. Food Chem. 58 (16), 9092–9102.

Cepeda-Lopez, A., Melse-Boonstra, A., Zimmermann, M., Herter-Aeberli, I., 2015. In overweight and obese women, dietary iron absorption is reduced and the enhancement of iron absorption by ascorbic acid is one-half that in normal-weight women. Am. J. Clin. Nutr. 102 (6), 1389–1397.

Chowa, S., Chiutsi, G., Mwangwela, A., 2021. Effectiveness of Community Learning and Growth Monitoring Sessions as a Tool for Promoting Appropriate Infant and Young Child Feeding Practices among Agro-Ecological Intensification Farmers-a Case of Linthipe and Golomoti EPAs in Dedza. Lilongwe University of Agriculture and Natural Resources, Malawi.

Combs, G., 2022. Reflecting on 'selenium in global food systems'. Br. J. Nutr. 127 (5), 736–738.

de Valença, A., Bake, A., Brouwer, I., Giller, K., 2017. Agronomic biofortification of crops to fight hidden hunger in sub-Saharan Africa. Glob. Food Sec. 12, 8–14.

Demeke, M., Meerman, J., Scognamillo, A., Romeo, A., Asfaw, S., 2016. Linking farm diversification to household diet diversification: evidence from a sample of Kenyan ultra-poor farmers. Food Secur. 8 (6), 1069–1085.

Dewey, K., Yang, Z., Boy, E., 2009. Systematic review and meta-analysis of home fortification of complementary foods. Matern. Child Nutr. 6;5 (4), 283–321.

Fan, M.S., Zhao, F.J., Fairweather-Tait, S.J., Poulton, P.R., Dunham, S.J., McGrath, S.P., 2008. Evidence of decreasing mineral density in wheat grain over the last 160 years. J. Trace Elem. Med. Biol. 22 (4), 315–324. https://doi.org/10.1016/j.jtemb.2008.07.002.

Food and Agriculture Organization of the United Nations, 2015. Designing Nutrition-Sensitive Agriculture Investments: Checklist and Guidance for Programme Formulation. FAO, Rome. https://www.fao.org/3/i5107e/i5107e.pdf.

Gashu, D., Nalivata, P.C., Amede, T., Ander, E.L., Bailey, E.H., Botoman, L., Chagumaira, C., Gameda, S., Haefele, S.M., Hailu, K., Joy, E.J.M., Kalimbira, A.A., Kumssa, D.B., Lark, R.M., Ligowe, I.S., McGrath, S.P., Milne, A.E., Mossa, A.W., Munthali, M., Towett, E.K., Walsh, M.G., Wilson, L., Young, S.D., Broadley, M.R., 2021. The nutritional quality of cereals varies geospatially in Ethiopia and Malawi. Nature 594 (7861), 71–76.

Gerrano, A.S., Mbuma, N.W., Mumm, R.H., 2022. Expression of nutritional traits in vegetable cowpea grown under various south African agro-ecological conditions. Plants 11 (11), 1422.

Giller, K., Delaune, T., Silva, J., Descheemaeker, K., van de Ven, G., Schut, A.G., van Ittersum, M., 2021. The future of farming: who will produce our food? Food Secur. 13 (5), 1073–1099.

Glahn, R.P., Wiesinger, J.A., Lung'aho, M.G., 2020. Iron concentrations in biofortified beans and nonbiofortified marketplace varieties in East Africa are similar. J. Nutr. 150 (11), 3013–3023.

Hall, C.M., Rasmussen, L.V., Powell, B., Dyngeland, C., Jung, S., Olesen, R.S., 2022. Deforestation reduces fruit and vegetable consumption in rural Tanzania. Proc. Natl. Acad. Sci. 119 (10), e2112063119.

Hallberg, L., Brune, M., Rossander, L., 1989. Iron absorption in man: ascorbic acid and dose-dependent inhibition by phytate. Am. J. Clin. Nutr. 49 (1), 140–144.

Halweil, B., 2007. Still no free lunch: nutrient levels in U.S. food supply eroded by pursuit of high yields. In: The Organic Center Critical Issue Report, September 2007. https://organic-center.org/still-no-free-lunch-nutrient-levels-us-food-supply-eroded-pursuit-high-yields.

Hepperly, P., Omondi, E., Seidel, R., 2018. Soil regeneration increases crop nutrients, antioxidants and adaptive responses. MOJ Food Proc. Technol 6 (2), 196–203.

Hogan, C., Perkins, A., 2022. Selenoproteins in the human placenta: how essential is selenium to a healthy start to life? Nutrients 14 (3), 628.

Hummel, M., 2020. Exploratory study on the barriers and enablers for implementation and consumption of (biofortified) beans in Malawi. In: Biofortification for Better Nutrition: Developing and Delivering Crops With More Impact, 126.

Jordan, I., Röhlig, A., Maria, G., Waswa, L., Mugisha, J., Krawinkel, M., Nuppenau, E., 2022. Dietary diversity of women across agricultural seasons in the Kapchorwa district, Uganda: results from a cohort study. Foods 11 (3), 344.

Joy, E., Ander, E., Young, S., Black, C., Watts, M., Chilimba, A., Chilima, B., Siyame, E., Kalimbira, A., Hurst, R., Fairweather-Tait, S., Stein, A., Gibson, R., White, P., Broadley, M., 2014. Dietary mineral supplies in Africa. Physiol. Plant. 151 (3), 208–229.

Joy, E., Kalimbira, A., Sturgess, J., Banda, L., Chiutsi-Phiri, G., Manase, H., Allen, E., 2022. Biofortified maize improves selenium status of women and children in a rural community in Malawi: results of the addressing hidden hunger with agronomy randomized controlled trial. Front. Nutr. 8, 1189.

Kelly, S., Bateman, A., 2010. Comparison of mineral concentrations in commercially grown organic and conventional crops – tomatoes (Lycopersicon esculentum) and lettuces (Lactuca sativa). Food Chem. 119 (2), 738–745.

Kihara, J., Sileshi, G., Nziguheba, G., Kinyua, M., Zingore, S., Sommer, R., 2017. Application of secondary nutrients and micronutrients increases crop yields in sub-Saharan Africa. Agron. Sustain. Dev. 37, 1–14.

Kihara, J., Bolo, P., Kinyua, M., Rurinda, J., Piikki, K., 2020. Micronutrient deficiencies in African soils and the human nutritional nexus: opportunities with staple crops. Environ. Geochem. Health 42, 3015–3033.

Kiran, A., Wakeel, A., Mahmood, K., Mubaraka, R., Hafsa, Haefele, S.M., 2022. Biofortification of staple crops to alleviate human malnutrition: contributions and potential in developing countries. Agronomy 12 (2), 452.

Klassen-Wigger, P., Geraets, M., Messier, M.C., Detzel, P., Lenoble, H.P., Barclay, D.V., 2018. Micronutrient fortification of bouillon cubes in central and West Africa. In: Food Fortification in a Globalized World. Academic Press, pp. 363–372.

Knez, M., Stangoulis, J., 2021. Calcium biofortification of crops-challenges and projected benefits. Front. Plant Sci. 12, 669053.

Koffi, C.K., Lourme-Ruiz, A., Djoudi, H., Bouquet, E., Dury, S., Gautier, D., 2020. The contributions of wild tree resources to food and nutrition security in sub-Saharan African drylands: a review of the pathways and beneficiaries. Int. For. Rev. 22 (1), 64–82.

Lemoine, A., Tounian, P., 2020. Childhood anemia and iron deficiency in sub-Saharan Africa–risk factors and prevention: a review. Arch. Pediatr. 27 (8), 490–496.

Ligowe, I., Phiri, F., Ander, E., Bailey, E., Chilimba, A., Gashu, D., Broadley, M., 2020. Selenium deficiency risks in sub-Saharan African food systems and their geospatial linkages. Proc. Nutr. Soc. 79 (4), 457–467.

Ligowe, I., Bailey, E., Young, S., Ander, E., Kabambe, V., Chilimba, A., Nalivata, P., 2021. Agronomic iodine biofortification of leafy vegetables grown in vertisols, oxisols and alfisols. Environ. Geochem. Health 43 (1), 361–374.

Likoswe, B.H., Joy, E.J., Sandalinas, F., Filteau, S., Maleta, K., Phuka, J.C., 2021. Re-defining the population-specific cut-off mark for vitamin A deficiency in pre-school children of Malawi. Nutrients 13 (3), 849.

Low, J., Mwanga, R., Andrade, M., Carey, E., Ball, A., 2017. Tackling vitamin a deficiency with biofortified sweet potato in sub-Saharan Africa. Food Securit. Governan. Latin America 14, 23–30.

Malézieux, E., Verger, E.O., Avallone, S., Ngigi, P.B., Lourme-Ruiz, A., Bazile, D., Amiot, M.J., 2023. Biofortification versus diversification to fight micronutrient deficiencies: an interdisciplinary review. Food Secur. 1–15.

Manzeke, M.G., Mtambanengwe, F., Watts, M.J., Hamilton, E.M., Lark, R.M., Broadley, M.R., Mapfumo, P., 2019. Fertilizer management and soil type influence grain zinc and iron concentration under contrasting smallholder cropping systems in Zimbabwe. Sci. Rep. 9 (1), 6445.

Manzeke-Kangara, M.G., Joy, E.J., Lark, R.M., Redfern, S., Eilander, A., Broadley, M.R., 2023. Do agronomic approaches aligned to regenerative agriculture improve the micronutrient concentrations of edible portions of crops? A scoping review of evidence. Front. Nutr. 10, 1078667.

Martínez-Ballesta, M., Dominguez-Perles, R., Moreno, D., Muries, B., Alcaraz-Lopez, C., Bastias, E., Carvajal, M., 2010. Minerals in plant food: effect of agricultural practices and role in human health. A review. Agron. Sustain. Dev. 30 (2), 295–309.

Ministry of Health, Community Development, Gender, Elderly and Children (MoHCDGEC) [Tanzania Mainland], Ministry of Health (MoH) [Zanzibar], Tanzania Food and Nutrition Centre (TFNC), National Bureau of Statistics (NBS), Office of the Chief Government Statistician (OCGS) [Zanzibar] and UNICEF, 2018. Tanzania National Nutrition Survey Using SMART Methodology (TNNS) 2018. MoHCDGEC, MoH, TFNC, NBS, OCGS, and UNICEF, Dar es Salaam, Tanzania. https://www.unicef.org/tanzania/media/2141/file/Tanzania%20National%20Nutrition%20Survey%202018.pdf.

Montgomery, D., Biklé, A., 2021. Soil health and nutrient density: beyond organic vs. conventional farming. Front. Sustain. Food Syst. 5, 699147.

Mozafar, A., 1994. Plant Vitamins: Agronomic, Physiological, and Nutritional Aspects, 1st ed. CRC Press.

Munthali, J., Fungo, R., Chirwa, R., Onyango, P., Rubyogo, J., 2020. High iron and zinc beans: kicking hidden hunger out of Malawi. Malawi Policy Brief 1–8. https://cgspace.cgiar.org/bitstream/handle/10568/110899/High_Munthali_2020.pdf?sequence=1.

Musumba, M., Grabowski, P., Palm, C., Snapp, S., 2017. Guide for the Sustainable Intensification Assessment Framework. https://www.k-state.edu/siil/resources/framework/index.html.

Mutambu, D., Kihara, J., Mucheru-Muna, M., Bolo, P., Kinyua, M., 2023. Maize grain yield and grain zinc concentration response to zinc fertilization: a meta-analysis. Heliyon 9, e16040.

Muthayya, S., Rah, J., Sugimoto, J., Roos, F., Kraemer, K., Black, R., 2013. The global hidden hunger indices and maps: an advocacy tool for action. PLoS One 8 (6), e67860.

Mutonhodza, B., Joy, E., Bailey, E., Lark, M., Kangara, M., Broadley, M., Chopera, P., 2022. Linkages between soil, crop, livestock, and human selenium status in sub-Saharan Africa: a scoping review. Int. J. Food Sci. Technol. 57 (10), 6336–6349.

Mzumara, E., 2016. Phosphorus Use Efficiency and Productivity of Pigeonpea (*Cajanus cajan* (L.) Millsp.) and Soybean (glycine Max (L.) Merrill) on Smallholder Farms in Different Agro-Ecological Zones of Central Malawi (Masters thesis,. Lilongwe University of Agriculture and Natural Resources.

National Statistical Office (NSO), Community Health Sciences Unit (CHSU) [Malawi], Centers for Disease Control and Prevention (CDC), and Emory University, 2016. Malawi Micronutrient Survey 2015–16: Key Indicators Report. NSO, CHSU, CDC and Emory University, Atlanta, GA, USA. http://www.nsomalawi.mw/images/stories/data_on_line/demography/mns2015_16/Malawi%20Micronutrient%20Survey%20Key%20Indicators%20Report.pdf.

Ngigi, P., Du, L., Masinde, P., Lachat, C., 2020. Selenium deficiency risk in Central Kenya highlands: an assessment from the soil to the body. Environ. Geochem. Health 42 (7), 2233–2250.

Nkhata, S., Chilungo, S., Memba, A., Mponela, P., 2020. Biofortification of maize and sweetpotatoes with provitamin a carotenoids and implication on eradicating vitamin a deficiency in developing countries. J. Agricult. Food Res. 2, 100068.

Noulas, C., Tziouvalekas, M., Karyotis, T., 2018. Zinc in soils, water and food crops. J. Trace Elem. Med. Biol. 49, 252–260.

Nube, M., Voortman, R., 2006. Simultaneously Addressing Micronutrient Deficiencies in Soils, Crops, Animal and Human Nutrition: Opportunities for Higher Yields and Better Health. Center for World Food Studies. Staff Working Paper.

Ochieng, J., Afari-Sefa, V., Lukumay, P., Dubois, T., 2017. Determinants of dietary diversity and the potential role of men in improving household nutrition in Tanzania. PLoS One 12 (12), e0189022.

Oniang'o, R., Mukudi, E., 2002. "Nutrition and Gender" Brief 7. In: Nutrition: A Foundation for Development. United Nations Administrative Committee on Coordination Sub-Committee on Nutrition. https://ebrary.ifpri.org/utils/getfile/collection/p15738coll2/id/92702/filename/92703.pdf.

Otani, T., Ae, N., Tanaka, H., 1996. Phosphorus (P) uptake mechanisms of crops grown in soils with low P status: II. Significance of organic acids in root exudates of pigeonpea. Soil Sci. Plant Nutr. 42 (3), 553–560.

Peramaiyan, P., Craufurd, P., Kumar, V., Seelan, L.P., McDonald, A., Balwinder-Singh, Singh, S., 2022. Agronomic biofortification of zinc in rice for diminishing malnutrition in South Asia. Sustainability 14 (13), 7747.

Phiri, F.P., Ander, E.L., Bailey, E.H., Chilima, B., Chilimba, A.D., Gondwe, J., Joy, E.J., Kalimbira, A.A., Kumssa, D.B., Lark, R.M., Phuka, J.C., 2019. The risk of selenium deficiency in Malawi is large and varies over multiple spatial scales. Sci. Rep. 9 (1), 6566.

Recena, R., García-López, A.M., Delgado, A., 2021. Zinc uptake by plants as affected by fertilization with Zn sulfate, phosphorus availability, and soil properties. Agronomy 11 (2), 390.

Rillig, M., Sosa-Hernández, M., Roy, J., Aguilar-Trigueros, C., Vályi, K., Lehmann, A., 2016. Towards an integrated mycorrhizal technology: harnessing mycorrhiza for sustainable intensification in agriculture. Front. Plant Sci. 7, 1625.

Ross, D., 2002. Recommendations for vitamin a supplementation. J. Nutr. 132 (9), 2902S–2906S.

Schiavon, M., Nardi, S., Dalla Vecchia, F., Ertani, A., 2020. Selenium biofortification in the 21st century: status and challenges for healthy human nutrition. Plant Soil 453, 245–270.

Sharma, I., Di Prima, S., Essink, D., Broerse, J., 2021. Nutrition-sensitive agriculture: a systematic review of impact pathways to nutrition outcomes. Adv. Nutr. 12 (1), 251–275.

Sibhatu, K.T., Qaim, M., 2018. Meta-analysis of the association between production diversity, diets, and nutrition in smallholder farm households. Food Policy 77, 1–18.

Snapp, S., Grabowski, P., Chikowo, R., Smith, A., Anders, E., Sirrine, D., Chimonyo, V., Bekunda, M., 2018. Maize yield and profitability tradeoffs with social, human and environmental performance: is sustainable intensification feasible? Agric. Syst. 162, 77–88.

Snapp, S., Dedecker, J., Davis, A., 2019. Farmer participatory research advances sustainable agriculture. Agronomy 111 (6), 2681–2691.

Stangoulis, J., Knez, M., 2022. Biofortification of major crop plants with iron and zinc - achievements and future directions. Plant Soil 474 (1–2), 57–76.

Strobbe, S., Van Der Straeten, D., 2018. Toward eradication of b-vitamin deficiencies: considerations for crop biofortification. Front. Plant Sci. 9, 443.

Strobbe, S., De Lepeleire, J., Der Straeten, Van, 2018. From *in planta* function to vitamin-rich food crops: the ace of biofortification. Front. Plant Sci. 9, 1862.

Szerement, J., Szatanik-Kloc, A., Mokrzycki, J., Mierzwa-Hersztek, M., 2022. Agronomic biofortification with se, Zn, and Fe: an effective strategy to enhance crop nutritional quality and stress defense—a review. J. Soil Sci. Plant Nutr. 22 (1), 1129–1159.

Tang, K., Adams, K.P., Ferguson, E.L., Woldt, M., Kalimbira, A.A., Likoswe, B., Joy, E.J., 2022. Modeling food fortification contributions to micronutrient requirements in Malawi using household consumption and expenditure surveys. Ann. N. Y. Acad. Sci. 1508 (1), 105–122.

Tang, K., Eilerts, H., Imohe, A., Adams, K.P., Sandalinas, F., Moloney, G., Hasman, A., 2023. Evaluating equity dimensions of infant and child vitamin a supplementation programmes using demographic and health surveys from 49 countries. BMJ Open 13 (3), e062387.

van Ginkel, M., Cherfas, J., 2023. What is wrong with biofortification. Global Food Security 37, 100689.

Velu, G., Crespo Herrera, L., Guzman, C., Huerta, J., Payne, T., Singh, R., 2019. Assessing genetic diversity to breed competitive biofortified wheat with enhanced grain Zn and Fe concentrations. Front. Plant Sci. 9.

Wang, M., Fan, L., Wei, W., Wang, P., Yu, Q., Long, Z., Wang, F., 2021. Integrated multi-omics uncovers reliable potential biomarkers and adverse effects of zinc deficiency. Clin. Nutr. 40 (5), 2683–2696.

Wang, L., Gao, F., Zhang, L., Zhao, L., Deng, Y., Guo, H., Wang, C., 2022. Effects of basal selenium fertilizer application on agronomic traits, yield, quality, and se content of dryland maize. Plants 11 (22), 3099.

Waraich, E., Ahmad, R., Ashraf, M., Saifullah, & Ahmad, M., 2011. Improving agricultural water use efficiency by nutrient management in crop plants. Acta Agricult. Scandinavica, Secti. B — Soil & Plant Sci. 61 (4), 291–304.

Welch, R., Graham, R., 2004. Breeding for micronutrients in staple food crops from a human nutrition perspective. J. Exp. Bot. 55 (396), 353–364.

Winder, M., Kosztyła, Z., Boral, A., Kocełak, P., Chudek, J., 2022. The impact of iodine concentration disorders on health and cancer. Nutrients 14 (11), 2209.

Zia, M.H., Ahmed, I., Bailey, E.H., Lark, R.M., Young, S.D., Lowe, N.M., Broadley, M.R., 2020. Site-specific factors influence the field performance of a Zn-biofortified wheat variety. Front. Sustain. Food Syst. 4, 135.

Zongho, K., Nethengwe, N., Mpandeli, N., Chikoore, H., 2022. Determinants of small-scale farmers' choice and adaptive strategies in response to climatic shocks in Vhembe district, South Africa. GeoJournal 87 (2), 677–700.

Zulu, S., Magwaza, L., Motsa, N., Sithole, N., Ncama, K., 2022. Long-term no-till conservation agriculture and nitrogen fertilization on soil micronutrients in a semi-arid region of South Africa. Agronomy 12 (6), 1411.