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# Biofortification versus diversification to fight micronutrient deficiencies: an interdisciplinary review

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## Summary

Two plant production-based strategies – biofortification and dietary diversification – have been advocated to overcome micronutrient deficiencies, which are major contributors to morbidity and mortality worldwide. The respective benefits and effectiveness of these two strategies are the subject of controversy. Expanding the scope of this debate beyond the sole nutritional outcomes, and using a food system approach, this interdisciplinary review aims at providing a novel and holistic perspective on the ongoing debate. The literature shows that biofortification can be an effective medium-term strategy to tackle nutritional risk in vulnerable populations in some contexts, but that it also may have negative environmental, economic, and social impacts. Dietary diversification, on the other hand, is known to be a sustainable way to overcome micronutrient deficiencies, bringing with it long-term benefits, including nutritional, and beyond, the provision of ecosystem services. Dietary diversification is however challenging to implement, with benefits that are not immediate. Biodiversity as a basis of human diets is critically important to improving both human and environmental health. Diet diversification through increased mobilisation of biodiversity in food systems deserves much more attention and support in policies for food and nutrition in low- and middle-income countries.

**Keywords** Biofortification · Diet diversification · Micronutrient deficiencies · Malnutrition · Food systems

## 1 Introduction

Vitamins and minerals are essential to adequate nutrition. Subclinical micronutrient deficiencies, often referred to as hidden hunger (Maberly et al., 1994; Messer, 1992),

increase both morbidity and mortality risks (Bailey et al., 2015). While the claim that 2 billion people worldwide are affected by micronutrient deficiencies has been made for over 30 years, a recent study suggested that this figure may actually be underestimated (Stevens et al., 2022). Along with undernutrition, overweight, obesity, and diet-related noncommunicable diseases, micronutrient deficiencies are part of the triple burden of malnutrition that undermines the opportunities and futures of individuals, as well as the prospect of achieving sustainable development for all. Since 1992, different strategies and policy recommendations to address micronutrient deficiencies have been issued by WHO and FAO (the World Health Organisation and Food and Agriculture Organisation of the United Nations, respectively; 1992, 2006). Among the recommended strategies, biofortification and dietary diversification are both food-based strategies to improve nutrition. However, the respective efficiency and sustainability of the two strategies are still subject of controversy among scientists and policy makers. The two strategies follow quite different agricultural development pathways, they involve different actors, lobbies,

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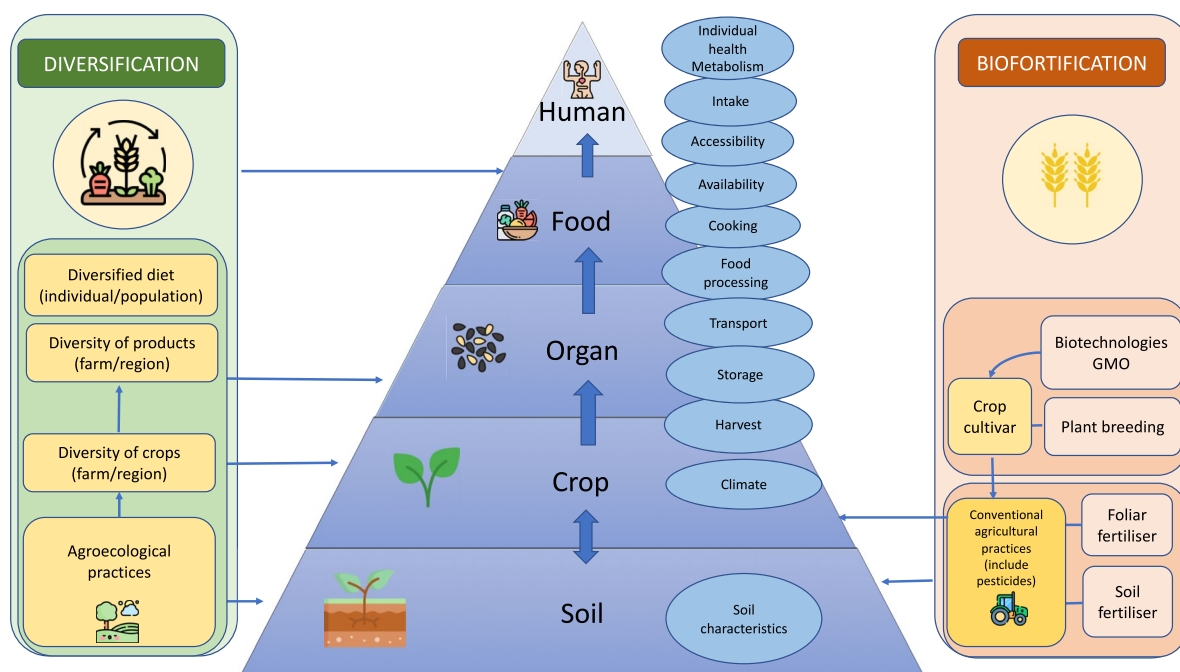
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agricultural practices, and ultimately, they imply stark differences in their underpinning visions regarding the role of agriculture in society (Fig. 1).

The aim of biofortification is to increase the nutritional density of vitamins and minerals in the edible part of the plants. Major staple crops are the main targets for biofortification. Biofortification may also aim to enhance food utilisation by improving nutrient bioavailability (Thompson & Amoroso, 2014). Biofortification initially focused on iron (Fe), zinc (Zn), and provitamin A because of their frequent inadequate dietary intakes in poor rural households and their negative health outcomes, notably anaemia, blindness, impaired physical and mental development, morbidity and mortality (Bouis et al., 2011). Biofortification uses two main approaches. The first is to apply fertilisers to increase nutrient uptake from the soil or via foliar applications, and improve the accumulation conditions in the edible parts of plants (Hirschi, 2009). Agronomic biofortification has been shown to increase the concentration of micronutrients including that of Fe, Zn and selenium (Se) in rice, wheat, corn, barley, sorghum, potato, soybean, and other legumes, and in vegetables including carrots, onion, and garlic (Fang

et al., 2008; Phattarakul et al., 2012; Wang et al., 2012). The second approach entails the insertion of biofortified plant varieties that accumulate higher levels of micronutrients in cropping systems. In the case of the main cereal crops used in intensive agriculture, this approach aims to address the limited micronutrient contents in varieties resulting from decades of breeding specifically aimed at increasing yields and amplified by climate change (Leisner, 2020). Different varieties of key food crops including rice, wheat, corn, barley, potato, tomato, and pulses have been biofortified with Fe, Zn, and vitamin A worldwide (Cakmak et al., 2017; Garg et al., 2018). These varieties are the result of conventional breeding (Saltzman et al., 2013), genetic engineering, and genome editing technologies (Garg et al., 2018).

Whereas biofortification focuses on one or a few nutrients at a time, dietary diversification considers a spectrum of micronutrients supplied through the consumption of a sufficient variety of foods. These include plant (fruit, vegetables, cereals, and legumes), and animal products (meat, or products of fisheries and aquaculture). Based on the principle that no single food can provide a sufficient quantity of all the nutrients required to maintain optimal health, eating a



**Fig. 1** Summary framework of two agricultural solutions to overcome micronutrient deficiencies: ‘Biofortification’ versus ‘Diversification’. Reducing micronutrient deficiencies by correcting the micronutrient content of food depends on a series of steps (blue triangle and large blue arrows), from the field (bottom of the triangle) to the consumer (top). Biofortification (right hand-side, orange box) consists in increasing the micronutrient content of staple crops. This can be achieved using different approaches e.g. transgenic, marker assisted, or conventional plant breeding, and different agricultural practices, including fertilisation to increase the micronutrient content in the edible organs, combined with other chemical inputs, such as pesticides.

Diversification (left, green box) acts at different steps and scales: agroecological practices (bottom) increase crop diversity at the farm and regional scales, thereby increasing the number of different farm products supplying a diversity of markets. Diversification of diets (left, top) influences micronutrient intakes. The final nutritional outcomes of both strategies depend on factors operating at the field to the consumer scales (blue ellipses). Figure 1 presents two contrasting agricultural pathways but intermediate pathways may exist: dietary diversification may co-exist within a regime of conventional agriculture, and biofortification may occur in low-input agriculture

variety of foods has been a longstanding public health recommendation worldwide.

Both biofortification and diversification are the subject of conflicting arguments and policies. On the one hand, it is argued that further breeding and transgenic programmes are required to develop new staple crop varieties capable of adapting to climate change, that produce high yields, and that are nutrient-enriched (Ofori et al., 2022). Such varieties should be grown by poor farmers using chemicals to increase the concentration of nutrients while protecting the crop against pathogens, animal pests, weeds and adverse effects of climate change (Maqbool et al., 2020). On the other hand, it also is argued that biofortification restricts nutrition to only a few nutrients; that it fails to address the root causes of undernutrition, which are linked to poverty and inequality; and that the best way to eliminate micronutrient deficiencies is to promote an increased supply and consumption of a wider range of foods (Graham et al., 2007).

Food systems are changing rapidly in low-income and middle-income countries (LMICs), in relation with growing populations and urbanisation. A food system “*gathers all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the output of these activities, including socio-economic and environmental outcomes*” (High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, 2017). Consequently, a food system approach encompasses the whole range of activities, drivers, and outcomes of a food system, their interconnections and interactions, and its actors (Ericksen, 2008; Sobal et al., 1998). Such an approach provides a more comprehensive view of the full range of consequences of any organisational choices in the food system, such as food-based strategies to improve nutrition (Tendall et al., 2015), or even the increase in risks and burdens of infectious diseases (Waage et al., 2022). In this article, we deconstruct the controversy between biofortification and diversification through an interdisciplinary prism using a food system approach. We review the results achieved by the two strategies reported in the literature through nutrition and health, agricultural, environmental, and social sciences lenses, before reconsidering the framework in a transdisciplinary perspective.

## 2 Biofortification versus diversification: Effects on nutrition and health

### 2.1 Biofortification, micronutrient intakes and status, impacts on health

The vast majority of studies on the potential of biofortification to reduce micronutrient deficiencies have focused

on three main micronutrients: Zn, Fe and provitamin A (Ofori et al., 2022). It has been estimated that biofortification has the potential to improve coverage of the estimated average requirement by 25% for zinc crops, 35% for iron crops, and > 85% for provitamin A crops (Van Der Straeten et al., 2020). Recent challenges concern the development of multinutrient biofortified maize to increase the likelihood of meeting recommended intakes of macro- and micronutrients thereby reducing multiple deficiencies (Goredema-Matongera et al., 2021; Van Der Straeten et al., 2020).

Changes in micronutrient status and health outcomes of individuals enrolled in randomized trials conducted in controlled conditions are required to evaluate the nutritional efficacy of biofortified crops. The literature reports contrasting results in children, women and general population (Table. 1). Biofortification appears to effectively improve the micronutrient status of children (Palmer et al., 2016a, b; Scott et al., 2018) and to have some beneficial effects on eye health (Palmer et al., 2016a), cognitive function (Scott et al., 2018), and diarrhea (Jones & De Brauw, 2015). No significant effects have been shown on either the zinc or iron status and anaemia in women (Murray-Kolb et al., 2017; Sazawal et al. (2018)). However, despite the lack of improvement in micronutrient status, some health benefits have been reported for cognitive performance (Murray-Kolb et al., 2017), morbidity, and a reduction in the number of days during which patients suffered from pneumonia, vomiting, and fever (Sazawal et al., 2018). In their systematic review and meta-analysis including only three randomised efficacy trials, Finkelstein et al. (2019) confirmed that the consumption of iron-biofortified crops can improve cognitive function, in terms of attention and memory. However, the authors did not observe any change in iron status, whereas the compilation of HarvestPlus biofortification trials reported an improvement in both iron status and vitamin A status (Bouis & Saltzman, 2017).

The relevance of biological indicators is often questioned in public health medicine, because each micronutrient is distributed throughout several body organs. Measuring one or two biological indicators therefore may not provide a complete picture of the nutritional effect of a single food.

The current state of play suggests that further studies are needed to: (i) assess the impact of storage, culinary, and consumption practices to ensure the nutritional advantage of biofortified crops (Van Der Straeten et al., 2020), (ii) evaluate the bioavailability of the nutrient concerned, which is influenced by a range of dietary factors (food matrix, co-existence of inhibitors and enhancers in the food and/or meal) and host (age, physio-pathological status microbiota, genetic variation), and (iii) confirm long-term health efficacy in real conditions while accounting for the variability caused by food and host factors (Ruel et al., 2018).

**Table 1** Summary of studies on the nutritional impact of biofortified crops

Authors	Country	Participant characteristics	Type of study	Biofortified crops	Outcomes	Key findings
Palmer et al. (2016b)	Zambia	4- to 8-y-old children ( <i>n</i> = 1024)	Cluster-randomized controlled trial	Provitamin A carotenoid–biofortified maize meal	Vitamin A status and deficiency	Increase in serum $\beta$ -carotene concentrations No effect on serum retinol and deficiency prevalence
Palmer et al. (2016a)	Zambia	4- to 8-y-old children ( <i>n</i> = 1024)	Cluster-randomized controlled trial	Provitamin A carotenoid–biofortified maize	Pupillary response	Improvement in pupillary responsiveness among children with marginal or deficient vitamin A status No effect on pupillary threshold or night blindness
Scott et al. (2018)	India	Boys and girls (12 to 16 years) 6 months ( <i>n</i> = 140)	Double-blind, randomized, intervention study	Iron-biofortified pearl millet	Hemoglobin, ferritin, transferrin receptor; body iron Cognitive function	Improvements in iron intakes, ferritin, transferrin receptor, body iron Improvement in attention, memory and reaction time
Jones and De Brauw (2015)	Mozambique	Children under 5-y-old ( <i>n</i> = 1321)	Cluster-randomized	Provitamin A orange sweet potatoes	Prevalence and duration of diarrhea	Reduction in diarrhea prevalence and duration
Murray-Kolb et al. (2017)	Rwanda	Women aged 18–27 y with low iron status 18 weeks ( <i>n</i> = 150)	Double-blind, randomized intervention	Iron biofortified beans	Iron status (hemoglobin, ferritin, transferrin receptor; body iron) Cognitive performance	No significant difference in hemoglobin and transferrin receptor concentration Positive effect on cognitive performance (speed of spatial selective attention, specificity of memory retrieval)
Sazawal et al. (2018)	India	Women of childbearing age and child pairs 6 months ( <i>n</i> = 6005)	Community based, double-masked randomized controlled trial	High zinc biofortified wheat flour	Plasma zinc status Morbidity Other diseases	No significant difference in zinc concentration Positive impact on self-reported morbidity Significant reduction in days with pneumonia, vomiting in children and fever in women of childbearing age
Finkelstein et al. (2019)	Philippines India Rwanda	General population (including pregnant or lactating women)	Systematic review and meta-analysis	Rice, pearl millet, and beans iron biofortified	Iron status (hemoglobin, serum ferritin, transferrin receptor; total body iron) Cognitive function	No significant effects on iron deficiency and anemia Improvement in cognitive performance (attention, memory) More beneficial effect on cognition in subjects suffering from iron deficiency at inclusion

*n* = number of participants involved in clinical trials

## 2.2 Dietary diversification

There is strong evidence in LMICs that diets that are mainly based on starchy staples with low consumption of fruits, vegetables, and animal-sourced products are associated with inadequate intakes of essential nutrients (Ruel, 2003). A recent review summarised evidence linking dietary diversity and dietary adequacy in adolescents and adults (Verger et al., 2021). Fifty studies reported that higher dietary diversity was positively associated with the nutritional adequacy of the diet in most cases, regardless of the economic context. Further, several studies in LMICs showed that higher dietary diversity was associated with reduced risk of micronutrient deficiencies: lower odds of vitamin A insufficiency resulting from consumption of meat, poultry, fish, fruit, and vegetables in Kenyan women of reproductive age (Fujita et al., 2012). Similarly, lower odds of Zn deficiency were achieved as a result of consumption of animal source foods in Ethiopian women of reproductive age (Gebremedhin et al., 2011); and reduced odds of insufficient Zn status resulted from consumption of meat, poultry, and fish in Mozambican adolescents (Korkalo et al., 2017). However, evidence that dietary diversity has a protective effect against anaemia in women of reproductive age in LMICs is conflicting: seven articles report association between higher dietary diversity with reduced odds of anaemia, whereas five report no association (Savy et al., 2006).

While there is consistent evidence that higher dietary diversity can prevent undernourishment in LMICs, as demonstrated in Burkina Faso (Lourme-Ruiz et al., 2021), the association between higher dietary diversity with body weight (insufficient or excessive), or with the risk of non-communicable diseases was found to be inconsistent in both adolescents and adults (Verger et al., 2021). However, evidence exists for a protective role of dietary diversity against some health outcomes (e.g. cardiovascular diseases) but not for others (e.g., type 2 diabetes; Mozaffari et al., 2021, 2022).

## 3 Biofortification versus diversification: Effects of nutritional strategies on the Agri-food system and the environment

### 3.1 Biofortification and Agri-food systems

All over the world, crop breeding programmes have always invested most efforts into increasing grain yields and producing more crops to increase land productivity, improve farmers' incomes and ultimately meet the demand of the ever-increasing human population. During the first Green

Revolution, the developing world witnessed an extraordinary period of increased food crop productivity, with the tripling of cereal crop productivity, with only a 30% increase in the surface area of cultivated land (Pingali, 2012). Over this period, the new varieties developed by international agricultural research centers in collaboration with national research programs have contributed to these large increases in crop productivity, although productivity gains and adoption have been uneven across crops and regions (Evenson & Gollin, 2003). Many staple crop species (not only cereals) today produce grains that are deficient in micronutrients, because of a negative correlation between (for cereals) grain weight, yield, and nutritional quality (Lata-Tenesaca et al., 2023; Mohan et al., 2023). To give but one example, wheat yields have more than doubled in many regions since the 1960s due to advances in plant breeding techniques and agronomy (Fischer et al., 2010; Grassini et al., 2013), however, the process has been accompanied by a decrease in concentration of Zn and Fe in the grains (Fan et al., 2008; Miner et al., 2022).

By the 1980s, the main objective was to adjust global food production to the growing demand for food by eliminating obstacles to crop production, particularly pests and diseases. Breeding to feed the world during the Green Revolution paved the way for the first period of GMOs in plant sciences (Buiatti et al., 2013). In contrast to the Green Revolution, the push for GMOs was based largely on private agricultural research, with varieties provided to farmers on market terms (Pingali & Raney, 2005). Increasing yields and consequently increasing the global food production (not uptake of micronutrients) was the first objective (Jacobsen et al., 2013). In this sense, biofortification is an attempt to reverse this tendency. Biofortification emerged as a possible solution in the global research system (Van Ginkel & Cherfas, 2023). In recent years, in particular since 2010, GMO breeding programmes have entered a second phase with new objectives with biofortification at the heart. The implementation of biofortification was supposed to offer several advantages: the increased production of basic crops, a positive sustainable impact on the environment, with the promotion of environmentally resistant breeding products, cheap breeding maintenance after the initial investment, and increased accessibility to rural and restricted areas (Dhaliwal et al., 2022). But assessment of the new biofortified GMO varieties must be improved to compare their nutritional contents with those of other modern crop varieties (high-yield varieties), especially tubercules, since data on cereals are already available (Ofori et al., 2022). There are several examples of biofortification combining high yields with high micronutrient levels (Ashokkumar et al., 2020; Duo et al., 2021; Velu et al., 2019). However, higher micronutrient content in genetically biofortified crops may be at the expense of yield (Raatz, 2018; Van Ginkel & Cherfas,

2023). Concentrations of minerals in grains depend on complex traits, controlled by multiple functional pathways, including absorption from the soil by roots, translocation from root to shoot and allocation to developing grain (Mori, 1999). Breeding for both high yield and micronutrient concentrations is challenging (Joukhadar et al., 2021). Breeding efforts are further complicated by the environment, soil type, and soil fertility, which all influence micronutrient accumulation (Lowe et al., 2020). As a result, biofortified varieties may require more nitrogen and more micronutrients in the environment (Zn or Fe) to express their potential. The introduction of high-yielding biofortified varieties in cropping systems has thus often required the intensification of these systems including increased use of chemical inputs and fossil energy, thereby increasing both farmers' dependency on the chemical industry and risks for the environment. Therefore, where agricultural soils are depleted (Stewart et al., 2020), biofortified crop varieties rely on the use of costly inputs. In the absence of government subsidies, smallholders revert to local landraces with lower market value (Snapp et al., 2018; Vidigal et al., 2020).

After the high cost of seed innovation (mainly covered by international programmes such as HarvestPlus, a CGIAR Challenge Programme <http://www.harvestplus.org>), the recurring costs of dissemination are assumed to be lower than those in other strategies (Bouis et al., 2011). However, while transgenic approaches account for more than 60% of the research on biofortification in terms of the number of cultivars released, the success rate remains low (Garg et al., 2018). National regulations limit the dissemination of the few varieties that are available. Once in place, the production and consumption of biofortified varieties largely depends on government and international funding. In practice, the cost-effectiveness of biofortification is often restricted to large-scale crop production and commercial seed supply systems. Further, the applicability of biofortification remains uncertain given the diversity of food cultures, weak seed systems, scarce and irregular processing, and cooking resources (Johns & Eyzaguirre, 2007).

Seed dependency should also be recognised as a major obstacle to the success of any biofortification strategy. This is particularly true of family farming of the Global South. Even if farmers receive the first seeds cost-free when biofortification programmes are launched, nothing is usually done to set up a long-term programme. In fact, farmers are forbidden to produce seeds for the following crop cycle because seeds are patented. Thus farmers' dependency on seed companies to be able to follow biofortification strategies is perpetuated (Cummings et al., 2023). What is more, farmers often have inadequate access to reliable information when choosing transgenic crops, some of which may be associated with toxic, allergenic, and genetic hazards, hence jeopardizing the very purpose of farming (Vega Rodríguez

et al., 2022; Zakaria et al., 2022). Indeed, adoption of these new GMOs biofortified varieties could put the nutritional security of the whole food system at risk by introducing new types of toxicity. The ethical principles of the right to informed choice should be respected, and many countries actually have taken precautionary measures for transgenic crops to avoid possible damage to the environment and health (Muzhinji & Ntuli, 2021).

Because of his focus on few cultivated varieties, biofortification might have adverse effects such as over-dependence on high calorie, starchy staples, which will ultimately erode agrobiodiversity in cropping systems (Bélanger & Pilling, 2019). The gradual replacement of locally adapted landraces or cultivars by few staple crops over-simplifies cropping and farming systems, making them vulnerable to global changes. The adaptive capacity of small-holders is jeopardised while their dependence on global commodities simultaneously increases (Katz-Rosene et al., 2023). This process may undermine efforts to conserve local neglected and underutilised species. Yet, neglected and underutilised species, including traditional fruits, vegetables and legumes, are often rich in micronutrients, adapted to local climatic and soil conditions, locally available and contribute significantly to nutrition security (Adhikari et al., 2017; Jacob et al., 2023; Massawe et al., 2015).

### 3.2 Dietary diversification and Agri-food systems

Diversification of agricultural production has been promoted as the most sustainable way to guarantee a more diversified diet for both farmers and the general population (High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, 2019). Yet, even though most studies show a positive link between agricultural and dietary diversity, the relationship is complex and depends to a great extent on the spatial scales and on the contexts. At farm level in LMICs, agrobiodiversity can increase the availability and accessibility of diversified food for poor farmers, particularly where agricultural biodiversity is low (Jones, 2017) e.g. in sub-Saharan Africa (Sibhatu & Qaim, 2018; Waha et al., 2022). Agricultural diversification can also provide farmers with additional income and different livelihood options, thereby increasing their resilience to the risk of seasonal shortage, natural disasters and price volatility (Thrupp, 2000). Farm income from the sale of agricultural products can also contribute to dietary diversity by making it possible to purchase food at markets (Dillon et al., 2015; Sibhatu et al., 2015). This seems especially true in Burkina Faso when the income is managed by women (Lourme-Ruiz et al., 2022). In the other extreme, where specialising in monocrops for export takes place, negative externalities affect the environment, increase farmers' incomes may not occur, and a negative effect on diets may take place. Indeed, specialisation

toward monocrops for export has been proven to reduce dietary diversity among cotton growers in Burkina Faso (Lourme-Ruiz et al., 2021, 2022) and to affect the nutritional status of the children of oil palm growers in Guatemala (Milovich & Villar, 2022).

Beyond providing food, agricultural diversification is an important lever to improve the sustainability of food systems at different scales. At the farm and regional scales, increasing agrobiodiversity may benefit farmers by improving agricultural productivity and providing ecosystem services (Beillouin et al., 2021; Malézieux et al., 2022). Crop diversity has also been identified as an effective way to cope with climate change-induced crop yield decrease and nutritional quality decline (Food and Agriculture Organization of United Nations, 2015). Agricultural diversification is furthermore often more labour-intensive, and so may increase rural employment opportunities especially for young people in LMICs, especially in sub-Saharan Africa, where rapid population growth and intense pressure on land occur (Giordano et al., 2019).

Promoting dietary diversity worldwide would encourage diversification of plant species worldwide. International trade contributes shaping food systems, either positively by enabling access to a wider range of foods in many countries, or negatively through the standardisation of diets and by reducing the number of species cultivated around the world (Khoury et al., 2014). At a global scale, the demand for, and the production of more diverse and nutrient-dense foods could reduce input-intensive monocropping in favor of the cultivation of vegetables, fruits, and legumes, as well as encouraging the conservation of traditional and indigenous plants (Fanzo et al., 2013). Recent studies point to certain levers, including reducing the consumption of red meat or sugar while increasing the consumption of fruit, vegetables, nuts, and legumes to ensure healthier diets and limit the environmental impacts of food systems (Beal et al., 2023; Coleman et al., 2021; Laine et al., 2021; Stylianou et al., 2021; Tilman & Clark, 2014; Willett et al., 2019).

#### 4 Biofortification and diversification from a political perspective

Diversification has long been under-promoted in the LMICs compared to biofortification and supplementation, which appear to be the preferred solutions in nutritional policies supported by the health sector (Delisle, 2003; Kimura, 2013; Van Ginkel & Chérfas, 2023). This observation is still valid today, although improving dietary diversity is now higher on political agendas as a result of the emergence of a multi-sectoral approach to nutrition and an interest in nutrition-sensitive agricultural interventions (Food and Agriculture Organization of United Nations, 2013; Food and Agriculture

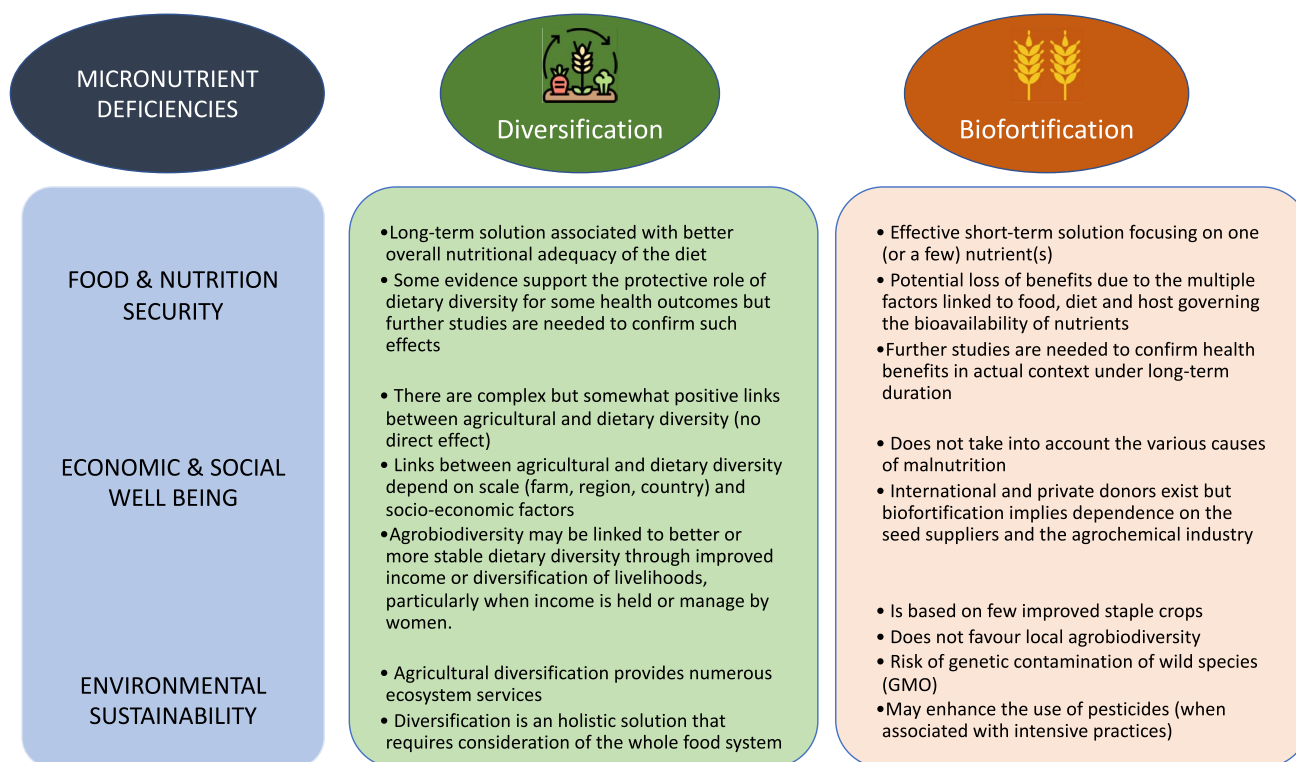
Organization of United Nations, 2017). It is worth noting that in many industrialised countries, diversified diets are strongly promoted by public authorities, sometimes through dietary guidelines, as is the case in the UK, France (Herberg et al., 2008), Australia (National Health and Medical Research Council, 2013) and several Scandinavian countries.

Biofortification and diversification involve different types of economic actors and are supported by asymmetric economic interests. Biofortification was developed through the HarvestPlus program, and was supported by a large international agricultural research consortium (CGIAR), with significant funding from large public and private donors including the World Bank, USAID, DANIDA, the ADB, and the Bill and Melinda Gates Foundation (Kimura, 2013). The HarvestPlus programme proposes a technology which also matches the interests of international seed and fertiliser companies and is apparently well received by policy makers, probably because it is a technology-driven approach that is perceived as a “magic bullet”, echoing the micronutrient movement of the 1990s with supplementation and food fortification (Horton and Wesley, 2008). Biofortification is also an explicit target for breeders as well as for governments and donors, which usually structure and orient their support for agriculture around a few priority value chains, mostly staples (Pingali, 2015). Apparent simplicity helps making biofortification very attractive to both policy makers and donors (Ginkel and Chérfas, 2023).

By contrast, dietary diversification involves a food system approach with multiple food chains, which are usually run by small-scale economic operators in the LMICs. Donors and states support a number of projects that aim to improve dietary diversity, however these projects are scattered across national territories and are implemented at relatively small scales. Unlike biofortification, dietary diversification projects do not involve large coalitions of powerful actors. In other words, a diversification strategy is not currently being promoted by any major international research programme supported by large-scale public and private donors and, perhaps most importantly, is not linked to any powerful economic interests. Political economy thus appears to help explain the imbalance in political interests and support for the two pathways.

Overall, actors promoting biofortification have benefited from a favourable political agenda on strengthening agriculture-nutrition linkages. Biofortification has been presented as a nutrition-sensitive agricultural intervention, and one which has been proved to be cost-effective compared to others actions aimed at improving dietary diversity (Ruel et al., 2018; Sharma et al., 2021). The amount of research using randomised controlled clinical trials to demonstrate the impact of biofortification on micronutrient status and its cost-effectiveness is then viewed as an advantage compared to research on other nutrition-sensitive agricultural





**Fig. 2** Potentials and limits of biofortification and diversification considering food and nutrition security, economic and social well-being, and environmental sustainability

interventions based on statistical correlation studies (Avalone et al., 2021; Ruel et al., 2018).

Each of the proposed pathways also has important consequences in terms of independence and national food sovereignty. Kimura (2013) and Scrinis (2016) show that biofortification is a solution over which countries suffering from food insecurity, and *a fortiori* their populations, have no control. Implementing biofortification would therefore make these countries dependent on technological systems and oligopolies. This criticism is similar to that of industrial agriculture, particularly by the early advocates of agroecology (e.g., Gliessman, 2016), who deplored farmers' dependence on seed companies, fertilisers, pesticides and, increasingly, on electronics and big data. The re-emergence of the question of food sovereignty following the Covid 19 crisis and the war in Ukraine has revived this criticism.

## 5 Conclusion

Figure 2 summarises the potential and limits of biofortification and of dietary diversification from the points of view of: (1) human health, (2) economic and social well-being, and (3) agricultural and environmental sustainability. Although biofortification may be an effective way to tackle specific micronutrient deficiencies, the strategy should be seen as a

short-term technical fix, whose potential may be reduced by complex bioavailability mechanisms and dietary behaviour. By contrast, diversification should be seen as a long-term strategy leading to improved overall nutritional adequacy.

Addressing the challenge of micronutrient deficiencies, but also of malnutrition in all its forms, requires a shift from a linear approach to a holistic, multidisciplinary, and multi-sector approach. Widespread use of biofortified foods as a way to tackle malnutrition not only oversimplifies the challenge posed by malnutrition, but could have serious consequences on the whole food system, with adverse impacts on the environment, in addition to social and economic impacts. Proposing a single-factor solution to an issue with multiple social, economic, and cultural roots fails to recognize the need for a profound transformation of food systems.

Diversification appears to be a solution that countries, farmers, and consumers can control. Unlike a stand-alone solution, diversification may be adapted to any different particular context, reflecting each specific agronomic and climatic characteristics, but also associating the local food cultures. Dietary diversification could thus enhance the sustainability of food systems at different scales. However, the implementation of diversification requires long-term structural and ambitious changes, such as the transformation of production systems, the organisation of efficient value chains for healthy but perishable foods, public regulations

favouring nutrient-rich foods, and improved consumer information. Successfully addressing these challenges requires a coordinated approach between public health, agriculture and consumers.

Regardless of the type of nutritional intervention strategy used, accounting for the broader food and consumption context is a prerequisite for sustainable nutrition and health. The key to good nutrition must remain a healthy, balanced diet, which in turn implies access to a variety of foods and the implementation of the right to food (Food and Agriculture Organization of United Nations, 2005). Malnutrition in LMICs is part of a global nexus where it combines with poverty and disease, within a strong frame of social and economic facts and constraints (Adeyeye et al., 2023; Owolade et al., 2022). Taking the agricultural, health, educational, and social aspects into consideration and addressing poverty reduction are part and parcel of any successful strategy.

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## Declarations

**Conflict of interest** The authors have no competing interests to declare that are relevant to the content of this article. They thank the anonymous reviewers for their careful reading of our manuscript and their many insightful comments and suggestions.

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## References

- Adeyeye, S. A. O., Ashaolu, T. J., Bolaji, O. T., Abegunde, T. A., & Omoyajowo, A. O. (2023). Africa and the Nexus of poverty, malnutrition and diseases. *Critical Reviews in Food Science and Nutrition*, 63(5), 641–656. <https://doi.org/10.1080/10408398.2021.1952160>
- Adhikari, L., Hussain, A., & Rasul, G. (2017). Tapping the potential of neglected and underutilized food crops for sustainable nutrition security in the mountains of Pakistan and Nepal. *Sustainability*, 9(2), 291. <https://doi.org/10.3390/su9020291>

- Ashokkumar, K., Govindaraj, M., Karthikeyan, A., Shobhana, V. G., & Warkentin, T. D. (2020). Genomics-integrated breeding for carotenoids and folates in staple cereal grains to reduce malnutrition. *Frontiers in Genetics*, 11, 414. <https://doi.org/10.3389/fgene.2020.00414>
- Avallone, S., Alpha, A., & Bricas, N. (2021). Fortifier les aliments pour lutter contre les carences? In N. Bricas, D. Conaré, & M. Walser (Eds.), *Une écologie de l'alimentation. Quae* <https://www.quae-open.com/extract/646>. Accessed 23 January 2023
- Bailey, R. L., West, K. P., Jr., & Black, R. E. (2015). The epidemiology of global micronutrient deficiencies. *Annals of Nutrition and Metabolism*, 66(Suppl. 2), 22–33. <https://doi.org/10.1159/000371618>
- Beal, T., Ortenzi, F., & Fanzo, J. (2023). Estimated micronutrient shortfalls of the EAT–lancet planetary health diet. *The Lancet Planetary Health*, 7(3), e233–e237. [https://doi.org/10.1016/S2542-5196\(23\)00006-2](https://doi.org/10.1016/S2542-5196(23)00006-2)
- Beillouin, D., Ben-Ari, T., Malézieux, E., Seufert, V., & Makowski, D. (2021). Positive but variable effects of crop diversification on biodiversity and ecosystem services. *Global Change Biology*, 27(19), 4697–4710. <https://doi.org/10.1111/gcb.15747>
- Bélanger, J., & Pilling, D. (2019). *The state of the World's biodiversity for food and agriculture*. FAO commission on genetic Resources for food and agriculture assessments.
- Bouis, H. E., & Saltzman, A. (2017). Improving nutrition through biofortification: A review of evidence from HarvestPlus, 2003 through 2016. *Global Food Security*, 12, 49–58. <https://doi.org/10.1016/j.gfs.2017.01.009>
- Bouis, H. E., Hotz, C., McClafferty, B., Meenakshi, J. V., & Pfeiffer, W. H. (2011). Biofortification: A new tool to reduce micronutrient malnutrition. *Food and Nutrition Bulletin*, 32(1\_suppl1), S31–S40. <https://doi.org/10.1177/15648265110321S105>
- Buiatti, M., Christou, P., & Pastore, G. (2013). The application of GMOs in agriculture and in food production for a better nutrition: Two different scientific points of view. *Genes & Nutrition*, 8(3), 255–270. <https://doi.org/10.1007/s12263-012-0316-4>
- Cakmak, I., Prom-u-thai, C., Guilherme, L. R. G., Rashid, A., Hora, K. H., Yazici, A., et al. (2017). Iodine biofortification of wheat, rice and maize through fertilizer strategy. *Plant and Soil*, 418(1–2), 319–335. <https://doi.org/10.1007/s11104-017-3295-9>
- Coleman, P. C., Murphy, L., Nyman, M., & Oyebo, O. (2021). Operationalising the EAT–Lancet commissions' targets to achieve healthy and sustainable diets. *The Lancet Planetary Health*, 5(7), e398–e399. [https://doi.org/10.1016/S2542-5196\(21\)00144-3](https://doi.org/10.1016/S2542-5196(21)00144-3)
- Cummings, C., Selfa, T., Lindberg, S., & Bain, C. (2023). Identifying public trust building priorities of gene editing in agriculture and food. *Agriculture and Human Values*. <https://doi.org/10.1007/s10460-023-10465-z>
- Delisle, H. (2003). Food diversification strategies are neglected in spite of their potential effectiveness: why is it so and what can be done? In 2ème Atelier international / 2nd International Workshop Voies alimentaires d'amélioration des situations nutritionnelles/ Food-based approaches for a healthy nutrition, Ouagadougou, 23–28 / 11 / 2003. Presented at the 2ème Atelier international / 2nd International Workshop Voies alimentaires d'amélioration des situations nutritionnelles/ Food-based approaches for a healthy nutrition, Ouagadougou, 23–28 / 11 / 2003, Ouagadougou
- Dhaliwal, S. S., Sharma, V., Shukla, A. K., Verma, V., Kaur, M., Shivay, Y. S., et al. (2022). Biofortification—A frontier novel approach to enrich micronutrients in field crops to encounter the nutritional security. *Molecules*, 27(4), 1340. <https://doi.org/10.3390/molecules27041340>
- Dillon, A., McGee, K., & Oseni, G. (2015). Agricultural production, dietary diversity and climate variability. *The Journal of Development Studies*, 51(8), 976–995. <https://doi.org/10.1080/00220388.2015.1018902>

- Duo, H., Hossain, F., Muthusamy, V., Zunjare, R. U., Goswami, R., Chand, G., et al. (2021). Development of sub-tropically adapted diverse provitamin-A rich maize inbreds through marker-assisted pedigree selection, their characterization and utilization in hybrid breeding. *PLoS One*, *16*(2), e0245497. <https://doi.org/10.1371/journal.pone.0245497>
- Ericksen, P. J. (2008). Conceptualizing food systems for global environmental change research. *Global Environmental Change*, *18*(1), 234–245. <https://doi.org/10.1016/j.gloenvcha.2007.09.002>
- Evenson, R. E., & Gollin, D. (2003). Assessing the impact of the green revolution, 1960 to 2000. *Science*, *300*(5620), 758–762. <https://doi.org/10.1126/science.1078710>
- 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. *Journal of Trace Elements in Medicine and Biology*, *22*(4), 315–324. <https://doi.org/10.1016/j.jtemb.2008.07.002>
- Fang, Y., Wang, L., Xin, Z., Zhao, L., An, X., & Hu, Q. (2008). Effect of foliar application of zinc, selenium, and iron fertilizers on nutrients concentration and yield of rice grain in China. *Journal of Agricultural and Food Chemistry*, *56*(6), 2079–2084. <https://doi.org/10.1021/jf800150z>
- Fanzo, J., Hunter, D., Borelli, T., & Mattei, F. (2013). In J. Fanzo (Ed.), *Diversifying food and diets: using agricultural biodiversity to improve nutrition and health* (1st ed.). Taylor & Francis.
- Finkelstein, J., Mehta, S., Villalpando, S., Mundo-Rosas, V., Luna, S., Rahn, M., et al. (2019). A randomized feeding trial of iron-biofortified beans on school children in Mexico. *Nutrients*, *11*(2), 381. <https://doi.org/10.3390/nu11020381>
- Fischer, R. A. (Tony), & Edmeades, G. O. (2010). Breeding and cereal yield Progress. *Crop Science*, *50*(S1). <https://doi.org/10.2135/cropsci2009.10.0564>
- Food and Agriculture Organization of United Nations. (2005). *The right to food*. Voluntary guidelines to support the progressive realization of the right to adequate food in the context of national food security. Accessed June 1, 2023, from <https://www.fao.org/3/y7937e/y7937e.pdf>
- Food and Agriculture Organization of United Nations. (2013). *Food systems for better nutrition*. FAO.
- Food and Agriculture Organization of United Nations. (2015). Voluntary guidelines to support the integration of genetic diversity into national climate change adaptation planning. Accessed May 23, 2023, from <https://www.fao.org/3/i4940e/i4940e.pdf>
- Food and Agriculture Organization of United Nations. (2017). *Nutrition-sensitive agriculture and food systems in practice: Options for intervention*. FAO. Accessed April 17, 2023, from <http://www.fao.org/3/i7848en/i7848EN.pdf>
- Fujita, M., Lo, Y.-J., & Baranski, J. R. (2012). Dietary diversity score is a useful indicator of vitamin A status of adult women in northern Kenya. *American Journal of Human Biology: The Official Journal of the Human Biology Council*, *24*(6), 829–834. <https://doi.org/10.1002/ajhb.22327>
- Garg, M., Sharma, N., Sharma, S., Kapoor, P., Kumar, A., Chunduri, V., & Arora, P. (2018). Biofortified crops generated by breeding, agronomy, and transgenic approaches are improving lives of millions of people around the world. *Frontiers in Nutrition*, *5*, 12. <https://doi.org/10.3389/fnut.2018.00012>
- Gebremedhin, S., Enquselassie, F., & Umeta, M. (2011). Prevalence of prenatal zinc deficiency and its association with socio-demographic, dietary and health care related factors in rural Sidama, southern Ethiopia: A cross-sectional study. *BMC Public Health*, *11*, 898. <https://doi.org/10.1186/1471-2458-11-898>
- Giordano, T., Losch, B., Sourisseau, J.-M., & Girard, P. (2019). Risks of mass unemployment and worsening of working conditions. *Food Systems at Risk*, *75*.
- Gliessman, S. (2016). Transforming food systems with agroecology. *Agroecology and Sustainable Food Systems*, *40*(3), 187–189. <https://doi.org/10.1080/21683565.2015.1130765>
- Goredema-Matongera, N., Ndhlela, T., Magorokosho, C., Kamutando, C. N., van Biljon, A., & Labuschagne, M. (2021). Multinutrient biofortification of maize (*Zea mays* L.) in Africa: Current status, opportunities and limitations. *Nutrients*, *13*(3), 1039. <https://doi.org/10.3390/nu13031039>
- Graham, R. D., Welch, R. M., Saunders, D. A., Ortiz-Monasterio, I., Bouis, H. E., Bonierbale, M., et al. (2007). Nutritious subsistence food systems. In D. L. Sparks (Ed.), *Advances in agronomy* (Vol. 92, pp. 1–74). Academic Press. [https://doi.org/10.1016/S0065-2113\(04\)92001-9](https://doi.org/10.1016/S0065-2113(04)92001-9)
- Grassini, P., Eskridge, K. M., & Cassman, K. G. (2013). Distinguishing between yield advances and yield plateaus in historical crop production trends. *Nature Communications*, *4*(1), 2918. <https://doi.org/10.1038/ncomms3918>
- Herberg, S., Chat-Yung, S., & Chauillac, M. (2008). The French National Nutrition and health program: 2001–2006–2010. *International Journal of Public Health*, *53*(2), 68–77. <https://doi.org/10.1007/s00038-008-7016-2>
- High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. (2017). *Nutrition and food systems*. HLPE.
- High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. (2019). *Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition*. (no. 14). HLPE.
- Hirschi, K. D. (2009). Nutrient biofortification of food crops. *Annual Review of Nutrition*, *29*(1), 401–421. <https://doi.org/10.1146/annurev-nutr-080508-141143>
- Horton, V., & Wesley. (2008). *Food fortification with iron and iodine*. Working paper/ Copenhagen Consensus Center.
- Jacob, M. C. M., Medeiros Souza, A., Martins De Carvalho, A., Alves De Vasconcelos Neto, C. F., Tregidgo, D., Hunter, D., et al. (2023). Food biodiversity as an opportunity to address the challenge of improving human diets and food security. *Ethnobiology and Conservation*. <https://doi.org/10.15451/ec2023-02-12.05-1-14>
- Jacobsen, S.-E., Sørensen, M., Pedersen, S. M., & Weiner, J. (2013). Feeding the world: Genetically modified crops versus agricultural biodiversity. *Agronomy for Sustainable Development*, *33*(4), 651–662. <https://doi.org/10.1007/s13593-013-0138-9>
- Johns, T., & Eyzaguirre, P. B. (2007). Biofortification, biodiversity and diet: A search for complementary applications against poverty and malnutrition. *Food Policy*, *32*(1), 1–24. <https://doi.org/10.1016/j.foodpol.2006.03.014>
- Jones, A. D. (2017). Critical review of the emerging research evidence on agricultural biodiversity, diet diversity, and nutritional status in low- and middle-income countries. *Nutrition Reviews*, *75*(10), 769–782.
- Jones, K. M., & De Brauw, A. (2015). Using agriculture to improve child health: Promoting Orange sweet potatoes reduces diarrhea. *World Development*, *74*, 15–24. <https://doi.org/10.1016/j.worlddev.2015.04.007>
- Joukhadar, R., Thistlethwaite, R., Trethowan, R. M., Hayden, M. J., Stangoulis, J., Cu, S., & Daetwyler, H. D. (2021). Genomic selection can accelerate the biofortification of spring wheat. *Theoretical and Applied Genetics*, *134*(10), 3339–3350. <https://doi.org/10.1007/s00122-021-03900-4>
- Katz-Rosene, R., Ortenzi, F., McAuliffe, G. A., & Beal, T. (2023). Levelling foods for priority micronutrient value can provide more meaningful environmental footprint comparisons. *Communications Earth & Environment*, *4*(1), 287. <https://doi.org/10.1038/s43247-023-00945-9>

- Khoury, C. K., Bjorkman, A. D., Dempewolf, H., Ramirez-Villegas, J., Guarino, L., Jarvis, A., et al. (2014). Increasing homogeneity in global food supplies and the implications for food security. *Proceedings of the National Academy of Sciences*, 111(11), 4001–4006.
- Kimura, A. H. (2013). *Hidden hunger: Gender and the politics of smarter foods*. Cornell University Press <https://library.oapen.org/handle/20.500.12657/30793>. Accessed 23 January 2023
- Korkalo, L., Erkkola, M., Heinonen, A. E., Freese, R., Selvester, K., & Mutanen, M. (2017). Associations of dietary diversity scores and micronutrient status in adolescent Mozambican girls. *European Journal of Nutrition*, 56(3), 1179–1189. <https://doi.org/10.1007/s00394-016-1167-3>
- Laine, J. E., Huybrechts, I., Gunter, M. J., Ferrari, P., Weiderpass, E., Tsilidis, K., et al. (2021). Co-benefits from sustainable dietary shifts for population and environmental health: An assessment from a large European cohort study. *The Lancet Planetary Health*, 5(11), e786–e796. [https://doi.org/10.1016/S2542-5196\(21\)00250-3](https://doi.org/10.1016/S2542-5196(21)00250-3)
- Lata-Tenesaca, L. F., De Mello Prado, R., Ajila-Celi, G. E., Da Silva, D. L., Junior, J. S. P., & Mattiuz, B.-H. (2023). Iron biofortification in quinoa: Effect of iron application methods on nutritional quality, anti-nutrient composition, and grain productivity. *Food Chemistry*, 404, 134573. <https://doi.org/10.1016/j.foodchem.2022.134573>
- Leisner, C. P. (2020). Review: Climate change impacts on food security - focus on perennial cropping systems and nutritional value. *Plant Science*, 293, 110412. <https://doi.org/10.1016/j.plantsci.2020.110412>
- Lourme-Ruiz, A., Dury, S., & Martin-Prével, Y. (2021). Linkages between dietary diversity and indicators of agricultural biodiversity in Burkina Faso. *Food Security*, 13(2), 329–349.
- Lourme-Ruiz, A., Koffi, C. K., Gautier, D., Bahya-Batinda, D., Bouquet, E., Dury, S., et al. (2022). Seasonal variability of women's dietary diversity and food supply: A cohort study in rural Burkina Faso. *Public Health Nutrition*, 25(9), 2475–2487. <https://doi.org/10.1017/S13688980021004171>
- Lowe, N. M., Zaman, M., Moran, V. H., Ohly, H., Sinclair, J., Fatima, S., et al. (2020). Biofortification of wheat with zinc for eliminating deficiency in Pakistan: Study protocol for a cluster-randomised, double-blind, controlled effectiveness study (BIZIFED2). *BMJ Open*, 10(11), e039231. <https://doi.org/10.1136/bmjopen-2020-039231>
- Maberly, G. F., Trowbridge, F. L., Yip, R., Sullivan, K. M., & West, C. E. (1994). Programs against micronutrient malnutrition: Ending hidden hunger. *Annual Review of Public Health*, 15(1), 277–301. <https://doi.org/10.1146/annurev.pu.15.050194.001425>
- Malézieux, E., Beillouin, D., & Makowski, D. (2022). Feeding the world better: Crop diversification to build sustainable food systems. *Perspective*, 58, 1–4.
- Maqbool, A., Abrar, M., Bakhsh, A., Çalıřkan, S., Khan, H. Z., Aslam, M., & Aksoy, E. (2020). Biofortification under climate change: The fight between quality and quantity. In S. Fahad, M. Hasanuz-zaman, M. Alam, H. Ullah, M. Saeed, I. Ali Khan, & M. Adnan (Eds.), *Environment, climate, plant and vegetation growth* (pp. 173–227). Springer International Publishing. [https://doi.org/10.1007/978-3-030-49732-3\\_9](https://doi.org/10.1007/978-3-030-49732-3_9) Accessed 24 January 2023.
- Massawe, F. J., Mayes, S., Cheng, A., Chai, H. H., Cleasby, P., Symonds, R., et al. (2015). The potential for underutilised crops to improve food security in the face of climate change. *Procedia Environmental Sciences*, 29, 140–141. <https://doi.org/10.1016/j.proenv.2015.07.228>
- Messer, E. (1992). Conference report - ending hidden hunger: A policy conference on micronutrient malnutrition. *Food and Nutrition Bulletin*, 14(1), 1–3. <https://doi.org/10.1177/156482659201400105>
- Milovich, J. Y., & Villar, E. (2022). Child undernutrition in Guatemala: Aggravating factors and levers. *So What?*, 21, 1–4.
- Miner, G. L., Delgado, J. A., Ippolito, J. A., Johnson, J. J., Kluth, D. L., & Stewart, C. E. (2022). Wheat grain micronutrients and relationships with yield and protein in the U.S. central Great Plains. *Field Crops Research*, 279, 108453. <https://doi.org/10.1016/j.fcr.2022.108453>
- Mohan, D., Mishra, C. N., Krishnappa, G., & Singh, G. P. (2023). Relevance of yield-related growth parameters in protein, iron and zinc and the prospects of their utilization for wheat (*Triticum aestivum* L.) improvement. *Cereal Research Communications*, 51(1), 225–236. <https://doi.org/10.1007/s42976-022-00289-8>
- Mori, S. (1999). Iron acquisition by plants. *Current Opinion in Plant Biology*, 2(3), 250–253. [https://doi.org/10.1016/S1369-5266\(99\)80043-0](https://doi.org/10.1016/S1369-5266(99)80043-0)
- Mozaffari, H., Hosseini, Z., Lafrenière, J., & Conklin, A. I. (2021). The role of dietary diversity in preventing metabolic-related outcomes: Findings from a systematic review. *Obesity Reviews*, 22(6). <https://doi.org/10.1111/obr.13174>
- Mozaffari, H., Hosseini, Z., Lafrenière, J., & Conklin, A. I. (2022). Is eating a mixed diet better for health and survival?: A systematic review and meta-analysis of longitudinal observational studies. *Critical Reviews in Food Science and Nutrition*, 62(29), 8120–8136. <https://doi.org/10.1080/10408398.2021.1925630>
- Murray-Kolb, L. E., Wenger, M. J., Scott, S. P., Rhoten, S. E., Lung'aho, M. G., & Haas, J. D. (2017). Consumption of iron-biofortified beans positively affects cognitive performance in 18- to 27-year-old rwandan female college students in an 18-week randomized controlled efficacy trial. *The Journal of Nutrition*, 147(11), 2109–2117. <https://doi.org/10.3945/jn.117.255356>
- Muzhinji, N., & Ntuli, V. (2021). Genetically modified organisms and food security in southern Africa: Conundrum and discourse. *GM Crops & Food*, 12(1), 25–35. <https://doi.org/10.1080/21645698.2020.1794489>
- National Health and Medical Research Council. (2013). *Australian Dietary Guidelines Summary*. National Health and Medical Research Council.
- Ofori, K. F., Antoniello, S., English, M. M., & Aryee, A. N. A. (2022). Improving nutrition through biofortification—A systematic review. *Frontiers in Nutrition*, 9, 1043655. <https://doi.org/10.3389/fnut.2022.1043655>
- Owolade, A. J.-J., Abdullateef, R. O., Adesola, R. O., & Olaloye, E. D. (2022). Malnutrition: An underlying health condition faced in sub Saharan Africa: Challenges and recommendations. *Annals of Medicine & Surgery*, 82. <https://doi.org/10.1016/j.amsu.2022.104769>
- Palmer, A. C., Healy, K., Barffour, M. A., Siamasantu, W., Chileshe, J., Schulze, K. J., et al. (2016a). Provitamin A carotenoid-biofortified maize consumption increases pupillary responsiveness among Zambian children in a randomized controlled trial. *The Journal of Nutrition*, 146(12), 2551–2558. <https://doi.org/10.3945/jn.116.239202>
- Palmer, A. C., Siamasantu, W., Chileshe, J., Schulze, K. J., Barffour, M., Craft, N. E., et al. (2016b). Provitamin A-biofortified maize increases serum  $\beta$ -carotene, but not retinol, in marginally nourished children: A cluster-randomized trial in rural Zambia. *The American Journal of Clinical Nutrition*, 104(1), 181–190. <https://doi.org/10.3945/ajcn.116.132571>
- Phattarakul, N., Rerkasem, B., Li, L. J., Wu, L. H., Zou, C. Q., Ram, H., et al. (2012). Biofortification of rice grain with zinc through zinc fertilization in different countries. *Plant and Soil*, 361(1–2), 131–141. <https://doi.org/10.1007/s11104-012-1211-x>
- Pingali, P. (2015). Agricultural policy and nutrition outcomes – Getting beyond the preoccupation with staple grains. *Food Security*, 7(3), 583–591. <https://doi.org/10.1007/s12571-015-0461-x>
- Pingali, P., & Raney, T. (2005). *From the green revolution to the gene revolution: How will the poor fare? (working paper no. ESA*

- working paper 05–09). Food and Agriculture Organization of the United Nations.
- Pingali, P. L. (2012). Green revolution: Impacts, limits, and the path ahead. *Proceedings of the National Academy of Sciences*, 109(31), 12302–12308. <https://doi.org/10.1073/pnas.0912953109>
- Raatz, B. (2018). Biofortification of grain legumes. *Achieving Sustainable Cultivation of Grain Legumes, 1*, 177–200. <https://doi.org/10.19103/as.2017.0023.06>
- Ruel, M. T. (2003). Operationalizing dietary diversity: A review of measurement issues and research priorities. *The Journal of Nutrition*, 133(11 Suppl 2), 3911S–3926S. <https://doi.org/10.1093/jn/133.11.3911S>
- Ruel, M. T., Quisumbing, A. R., & Balagamwala, M. (2018). Nutrition-sensitive agriculture: What have we learned so far? *Global Food Security*, 17, 128–153. <https://doi.org/10.1016/j.gfs.2018.01.002>
- Saltzman, A., Birol, E., Bouis, H. E., Boy, E., De Moura, F. F., Islam, Y., & Pfeiffer, W. H. (2013). Biofortification: Progress toward a more nourishing future. *Global Food Security*, 2(1), 9–17. <https://doi.org/10.1016/j.gfs.2012.12.003>
- Savy, M., Martin-Prével, Y., Traissac, P., Eymard-Duvernay, S., & Delpuech, F. (2006). Dietary diversity scores and nutritional status of women change during the seasonal food shortage in rural Burkina Faso. *The Journal of Nutrition*, 136(10), 2625–2632. <https://doi.org/10.1093/jn/136.10.2625>
- Sazawal, S., Dhingra, U., Dhingra, P., Dutta, A., Deb, S., Kumar, J., et al. (2018). Efficacy of high zinc biofortified wheat in improvement of micronutrient status, and prevention of morbidity among preschool children and women - a double masked, randomized, controlled trial. *Nutrition Journal*, 17(1), 86. <https://doi.org/10.1186/s12937-018-0391-5>
- Scott, S. P., Murray-Kolb, L. E., Wenger, M. J., Udipi, S. A., Ghugre, P. S., Boy, E., & Haas, J. D. (2018). Cognitive performance in Indian school-going adolescents is positively affected by consumption of Iron-biofortified pearl millet: A 6-month randomized controlled efficacy trial. *The Journal of Nutrition*, 148(9), 1462–1471. <https://doi.org/10.1093/jn/nxy113>
- Scrinis, G. (2016). Reformulation, fortification and functionalization: Big food corporations' nutritional engineering and marketing strategies. *Journal of Peasant Studies*, 43(1), 17–37. <https://doi.org/10.1080/03066150.2015.1101455>
- Sharma, I. K., Di Prima, S., Essink, D., & Broerse, J. E. W. (2021). Nutrition-sensitive agriculture: A systematic review of impact pathways to nutrition outcomes. *Advances in Nutrition*, 12(1), 251–275. <https://doi.org/10.1093/advances/nmaa103>
- Sibhatu, K. T., Krishna, V. V., & Qaim, M. (2015). Production diversity and dietary diversity in smallholder farm households. *Proceedings of the National Academy of Sciences of the United States of America*, 112(34), 10657–10662. <https://doi.org/10.1073/pnas.1510982112>
- Sibhatu, K. T., & Qaim, M. (2018). Review: Meta-analysis of the association between production diversity, diets, and nutrition in smallholder farm households. *Food Policy*, 77, 1–18. <https://doi.org/10.1016/j.foodpol.2018.04.013>
- Snapp, S., Rahmanian, M., & Batello, C. (2018). *Pulse crops for sustainable farms in sub-Saharan Africa*. United Nations <https://www.un-ilibrary.org/content/books/9789210472562>. Accessed 23 January 2023
- Sobal, J., Kettel Khan, L., & Bisogni, C. (1998). A conceptual model of the food and nutrition system. *Social Science & Medicine*, 47(7), 853–863. [https://doi.org/10.1016/S0277-9536\(98\)00104-X](https://doi.org/10.1016/S0277-9536(98)00104-X)
- Stevens, G. A., Beal, T., Mbuya, M. N. N., Luo, H., Neufeld, L. M., Addo, O. Y., et al. (2022). Micronutrient deficiencies among preschool-aged children and women of reproductive age worldwide: A pooled analysis of individual-level data from population-representative surveys. *The Lancet Global Health*, 10(11), e1590–e1599. [https://doi.org/10.1016/S2214-109X\(22\)00367-9](https://doi.org/10.1016/S2214-109X(22)00367-9)
- Stewart, Z. P., Pierzynski, G. M., Middendorf, B. J., & Prasad, P. V. V. (2020). Approaches to improve soil fertility in sub-Saharan Africa. *Journal of Experimental Botany*, 71(2), 632–641. <https://doi.org/10.1093/jxb/erz446>
- Stylianou, K. S., Fulgoni, V. L., & Jolliet, O. (2021). Small targeted dietary changes can yield substantial gains for human health and the environment. *Nature Food*, 2(8), 616–627. <https://doi.org/10.1038/s43016-021-00343-4>
- Tendall, D. M., Joerin, J., Kopainsky, B., Edwards, P., Shreck, A., Le, Q. B., et al. (2015). Food system resilience: Defining the concept. *Global Food Security*, 6, 17–23. <https://doi.org/10.1016/j.gfs.2015.08.001>
- Thompson, B., & Amoroso, L. (2014). *Improving diets and nutrition: Food-based approaches*. CABI. Accessed May 25, 2023, from <https://books.google.fr/books?id=Yf6dAwAAQBAJ>
- Thrupp, L. A. (2000). Linking agricultural biodiversity and food security: The valuable role of agrobiodiversity for sustainable agriculture. *International Affairs*, 76(2), 265–281. <https://doi.org/10.1111/1468-2346.00133>
- Tilman, D., & Clark, M. (2014). Global diets link environmental sustainability and human health. *Nature*, 515(7528), 518–522. <https://doi.org/10.1038/nature13959>
- Van Der Straeten, D., Bhullar, N. K., De Steur, H., Gruijssem, W., MacKenzie, D., Pfeiffer, W., et al. (2020). Multiplying the efficiency and impact of biofortification through metabolic engineering. *Nature Communications*, 11(1), 5203. <https://doi.org/10.1038/s41467-020-19020-4>
- Van Ginkel, M., & Chérfas, J. (2023). What is wrong with biofortification. *Global Food Security*, 37, 100689. <https://doi.org/10.1016/j.gfs.2023.100689>
- Vega Rodríguez, A., Rodríguez-Oramas, C., Sanjuán Velázquez, E., Hardisson De La Torre, A., Rubio Armendáriz, C., & Carrascosa Iruzubieta, C. (2022). Myths and realities about genetically modified food: A risk-benefit analysis. *Applied Sciences*, 12(6), 2861. <https://doi.org/10.3390/app12062861>
- Velu, G., Crespo Herrera, L., Guzman, C., Huerta, J., Payne, T., & Singh, R. P. (2019). Assessing genetic diversity to breed competitive biofortified wheat with enhanced grain Zn and Fe concentrations. *Frontiers in Plant Science*, 9, 1971. <https://doi.org/10.3389/fpls.2018.01971>
- Verger, E. O., Le Port, A., Borderon, A., Bourbon, G., Moursi, M., Savy, M., et al. (2021). Dietary diversity indicators and their associations with dietary adequacy and health outcomes: A systematic scoping review. *Advances in Nutrition*, 12(5), 1659–1672. <https://doi.org/10.1093/advances/nmab009>
- Vidigal, P., Manuel Romeiras, M., & Monteiro, F. (2020). Crops diversification and the role of orphan legumes to improve the sub-Saharan Africa farming systems. In M. Hasanuzzaman, M. C. M. T. Filho, M. Fujita, & T. A. R. Nogueira (Eds.), *Sustainable crop production*. IntechOpen <https://www.intechopen.com/books/sustainable-crop-production/crops-diversification-and-the-role-of-orphan-legumes-to-improve-the-sub-saharan-africa-farming-syste>. Accessed 27 January 2023

Waage, J., Grace, D., Fèvre, E. M., McDermott, J., Lines, J., Wieland, B., et al. (2022). Changing food systems and infectious disease risks in low-income and middle-income countries. *The Lancet Planetary Health*, 6(9), e760–e768. [https://doi.org/10.1016/S2542-5196\(22\)00116-4](https://doi.org/10.1016/S2542-5196(22)00116-4)

Waha, K., Accatino, F., Godde, C., Rigolot, C., Bogard, J., Domingues, J. P., et al. (2022). The benefits and trade-offs of agricultural diversity for food security in low- and middle-income countries: A review of existing knowledge and evidence. *Global Food Security*, 33, 100645. <https://doi.org/10.1016/j.gfs.2022.100645>

Wang, J., Mao, H., Zhao, H., Huang, D., & Wang, Z. (2012). Different increases in maize and wheat grain zinc concentrations caused by soil and foliar applications of zinc in loess plateau, China. *Field Crops Research*, 135, 89–96. <https://doi.org/10.1016/j.fcr.2012.07.010>

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al. (2019). Food in the Anthropocene: The EAT–lancet commission on healthy diets from sustainable food systems. *The Lancet*, 393(10170), 447–492.

World Health Organization & Food and Agriculture Organization of the United Nations. (1992). International Conference on Nutrition: final report of the Conference. In *International conference on nutrition. Presented at the International Conference on nutrition*. WHO. Accessed May 25, 2023, from <https://apps.who.int/iris/handle/10665/61254>

World Health Organization & Food and Agriculture Organization of the United Nations. (2006). *Guidelines on food fortification with micronutrients* (Lindsay Allen.). WHO. Accessed April 12, 2023, from <https://apps.who.int/iris/handle/10665/43412>

Zakaria, H., Abujaja, A. M., Quainoo, A. K., & Obeng, F. K. (2022). Knowledge and understanding about genetically modified (GM) crops among smallholder farmers in northern Ghana. *Journal of Agricultural Biotechnology and Sustainable Development*, 14(1), 10–23. <https://doi.org/10.5897/JABSD2021.0388>



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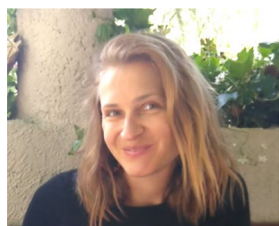
**Arlène Alpha** is a senior researcher at CIRAD, with specific expertise in policy design processes in food and nutrition security, especially in Sub-Saharan Africa. After her PhD in political economy, she worked during 12 years in NGOs as an agricultural and food security expert. Since 2012 at CIRAD, she specialized in research projects dealing with policies related to food security, nutrition, organic agriculture and agroecology. She spent 5 years (2014-2019) in Burkina Faso working on issues such as the inter-sectoral coordination

between Agriculture and Health to improve dietary diversity and the political agenda setting around agroecology. She is now based in South Africa, hosted by the Center of Excellence in Food Security at the University of the Western Cape, with a particular focus on policies supportive of food system transformations to combat the multiple forms of malnutrition.



**Peter Biu Ngigi** is a human nutritionist with a multidisciplinary research and working experience at the interface of agronomy, food science, nutrition, public health and ecosystem resilience. He is motivated by the linkages between different perspectives on food and its contemporary issues that influence dietary choices at different levels. He is greatly interested in initiatives that adopt a holistic and system-

atic food and nutrition security approach, and consider agri-food systems comprehensively from production to consumption and health outcomes. This includes the interrelationships between nutrition and human health, sustainable agriculture and food systems, ecosystem resilience and economic development. Currently, his focus is on contributing and promoting equitable transition towards healthy and sustainable diets produced by sustainable agri-food systems, within the framework of multidisciplinary approach.



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